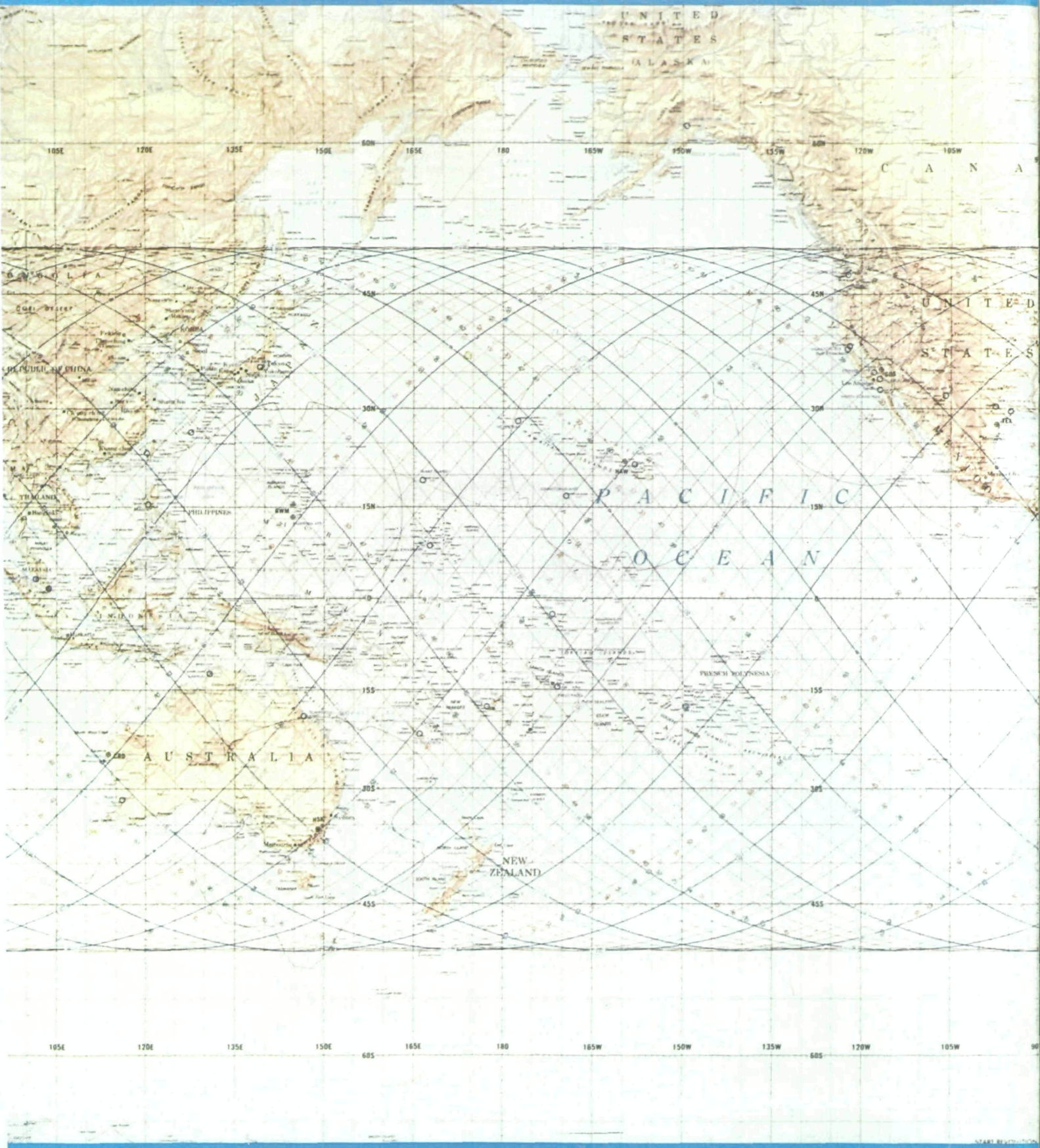
A NEW SUN
The Solar Results From Skylab

National Aeronautics and
Space Administration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A New Sun: The Solar Results From Skylab

NASA SP–402

A NEW SUN
The Solar Results From Skylab

By John A. Eddy

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Prepared by
George C. Marshall
Space Flight Center

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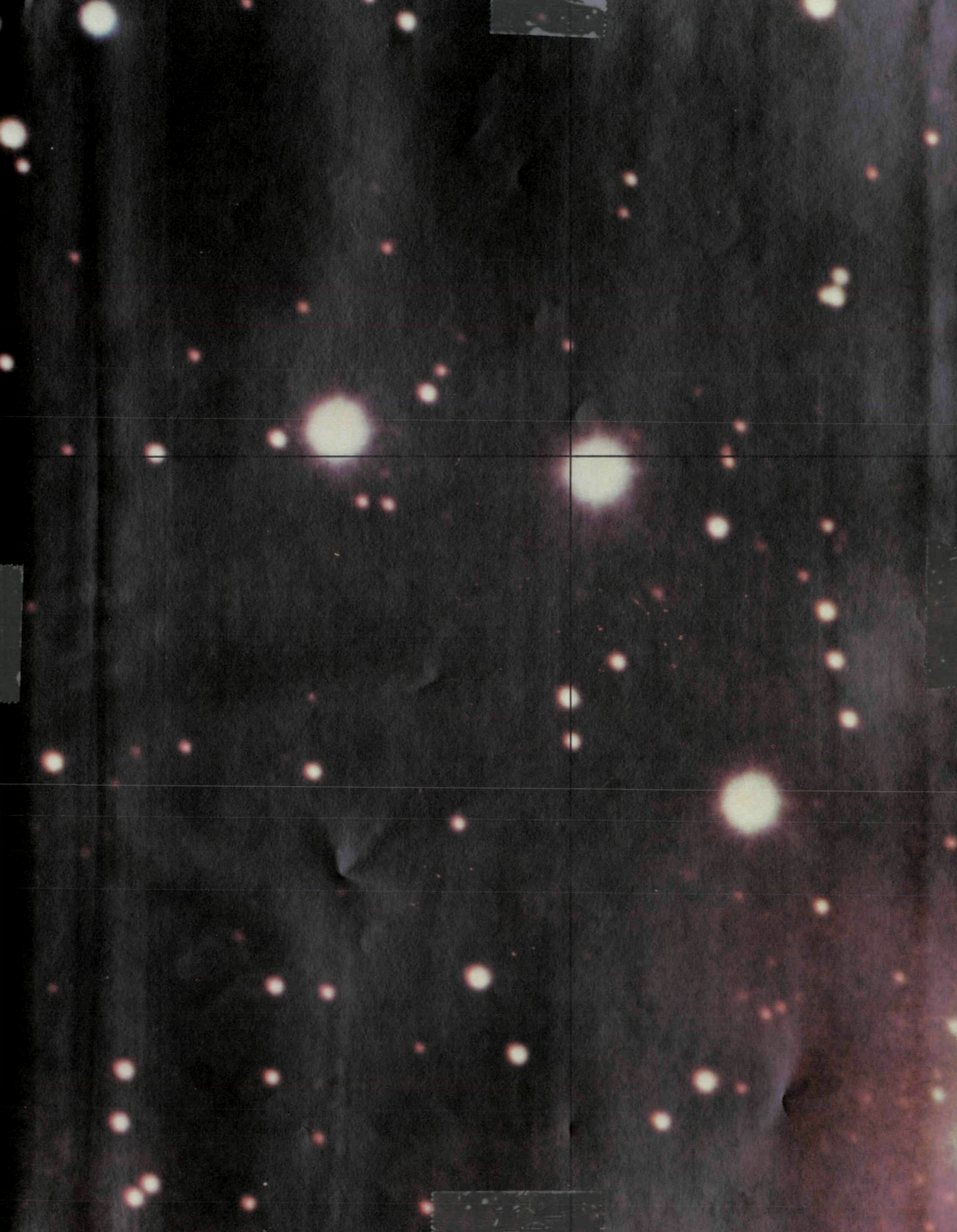
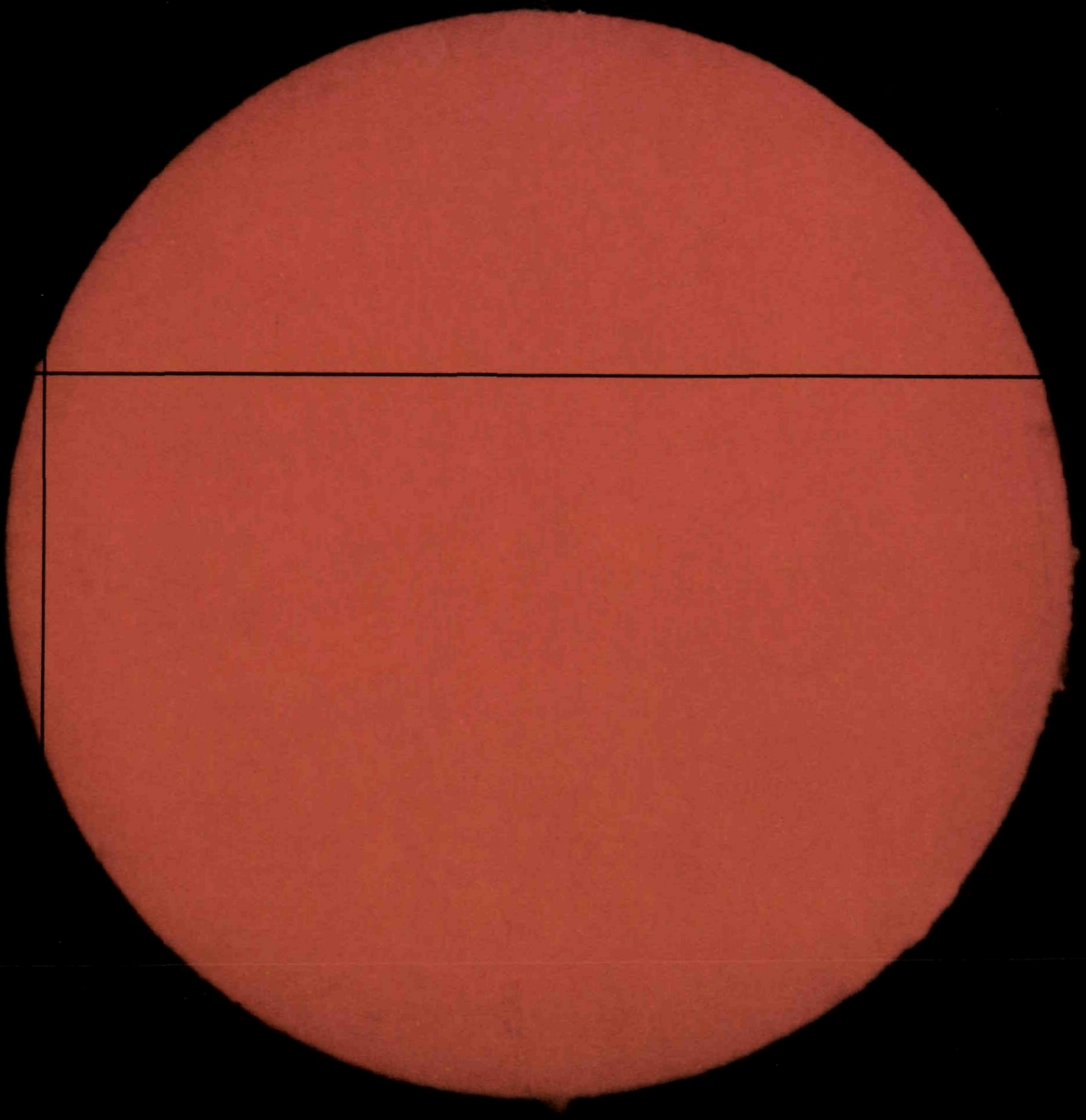




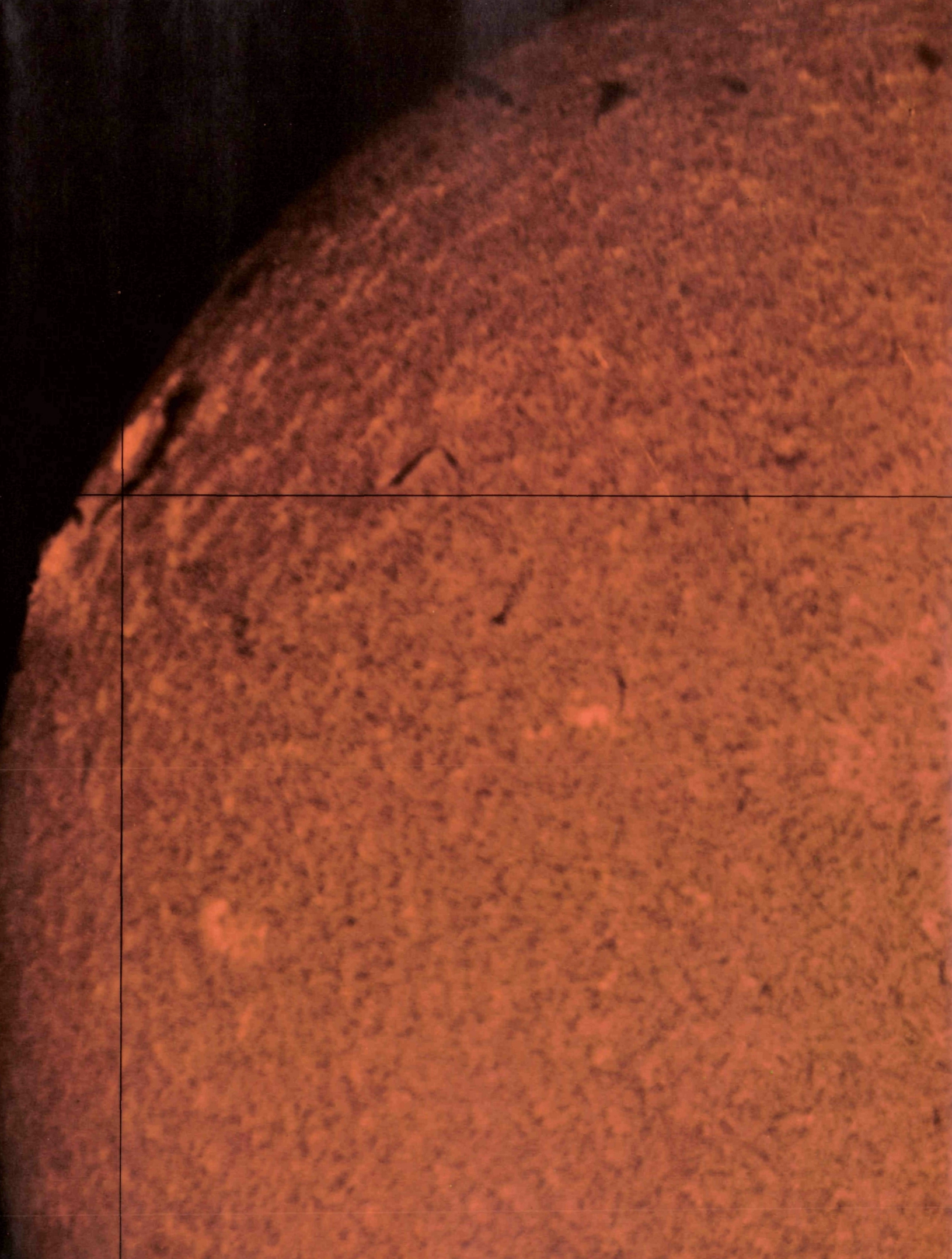
Foreword

The success of the Skylab mission and its Apollo Telescope Mount (ATM) has been a thrilling event to those of us who have been engaged with NASA since 1958 in planning and consummating solar research missions in space. Conceived in 1965 as a relatively simple exercise to test man's capability for doing useful work in space, the ATM concept was subjected to a continuous process of critical review, revision, and upgrading by NASA, working in concert with industry and the scientific community. The ATM that finally emerged became one of the most important milestones in the history of solar astrophysics. The mission in fact represented the final step in the initial long-term strategy for solar astrophysics that was set by the Space Science Board of the National Academy of Sciences in 1960, which called for the installation in space of a very large orbiting solar observatory, weighing several thousand megagrams and comparing favorably with ground-based observatories as regards lightgathering power and angular and spectroscopic resolution.

In terms of versatility, sensitivity, and reliability, the performance of the ATM telescopes and instruments exceeded the highest aspirations of astronomers during the 1960's. Yet, the mission appeared headed for total and complete disaster, until rescued by the heroic and skillful exploits of the astronauts in repairing the damage incurred by the spacecraft during launch. In this and other ways, the role of man in the operation of space observatories was clearly, even brilliantly, delineated.

The study of ATM observations has already led to many new discoveries about the nature of the Sun and about the fascinating events that occur on even a very ordinary star. Especially illuminating has been the recognition of the extent to which the Sun's magnetic field is responsible for the structure, dynamics, and heating of the Sun's outer layers. So massive was the harvest of information, however, that it will be many years before the possibilities for productive analyses are exhausted. I am confident that well before that time we shall have gained such entirely new perspectives on the Sun that we will be confronting a brand new set of questions and addressing them with a second generation of solar space experiments.

LEO GOLDBERG
Kitt Peak National Observatory



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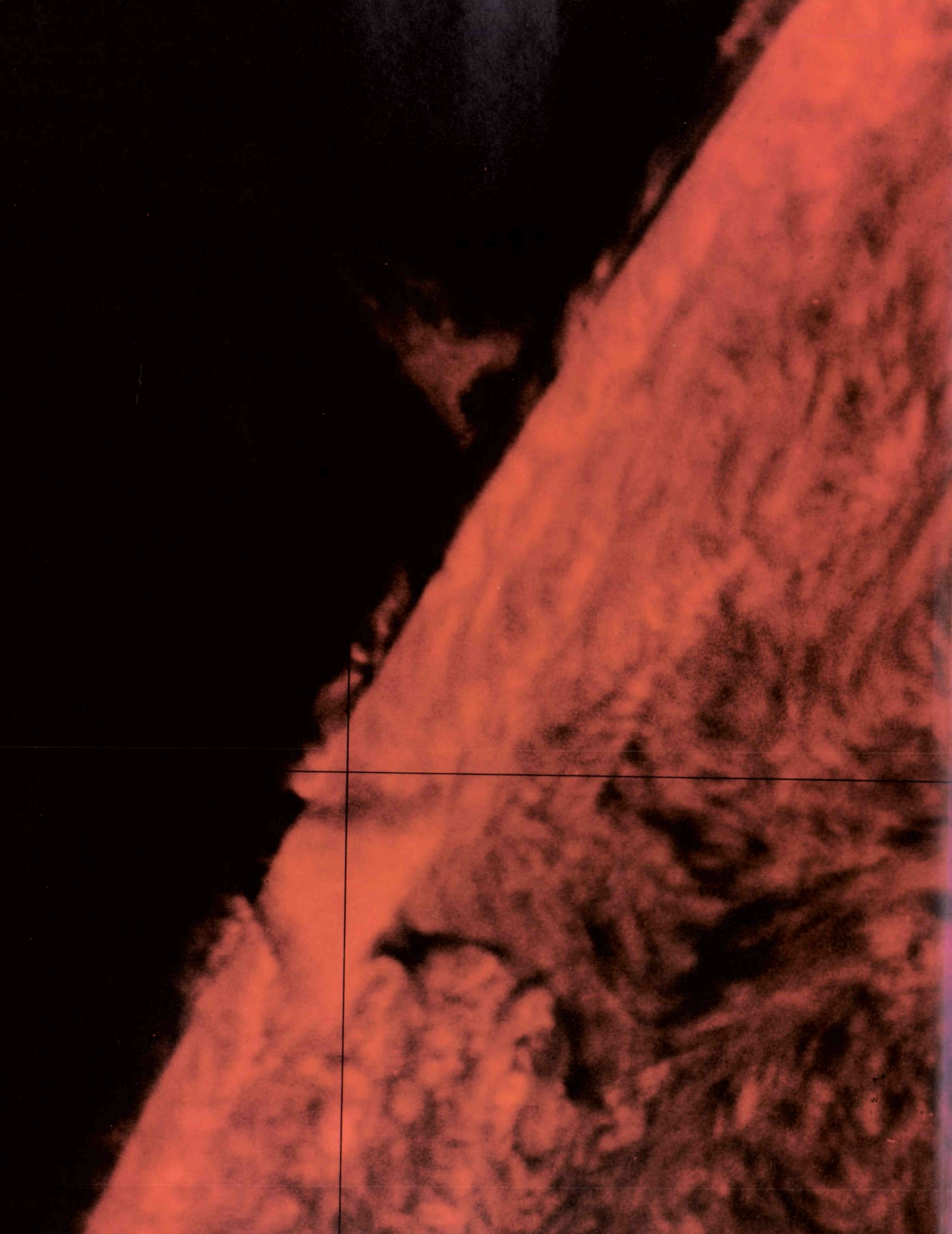

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OFF TO THE SUN! Astronauts Carr, Gibson, and Pogue blast off from Cape Kennedy on November 16, 1973, to rendezvous with Skylab, 435 km above Earth. They were the third and final crew to man the scientific space station and their stay of 84 days set an endurance record for man in space.

Introduction

*by Edward G. Gibson**

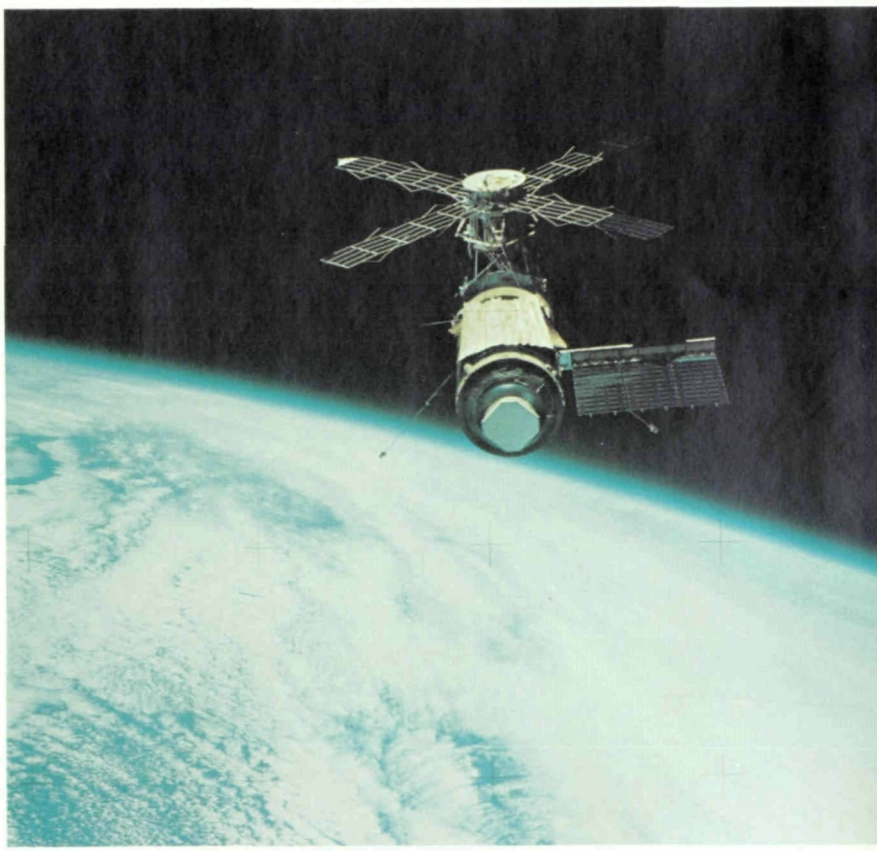
What you can do or deam you can, begin it: Boldness has genius, power, and magic in it.

—Goethe

It is November 16, 1973. We are 435 km above Earth, traveling over it at 8 km/sec. Slowly, our command module moves in and docks with Skylab. We have arrived at our country's first space station, a 91-Mg laboratory in orbit around our planet Earth.

Two crews have been here before us—they repaired the damaged laboratory, performed their programed observations successfully, and returned home. Now it is our turn. Peering through the command module windows, we can see the immense workshop, its solar-panel wings standing out starkly against the black sky. We anticipate with excitement (and to some degree, awe) our planned 56-day sojourn here. It turns out to be 84 days—nearly 3 months.

Looking back, I can again feel the excitement, the sense of challenge and adventure, of those first moments. Skylab offered the first two crews and us an opportunity to do what none had done before—to study the Sun from space. For one of the most exciting parts of the Skylab challenge was the operation of the great battery of solar telescopes on the Apollo Telescope Mount (ATM), part of the orbiting space station. For over 7 years I had been closely involved in the design, testing, and planning for these telescopes, and now I was to use them and to see the Sun as it could not be seen from Earth. Judging from the successes of the first two manned missions, we could anticipate discoveries



SKYLAB looked like this to astronauts Carr, Gibson, and Pogue as they approached it on November 16, 1973, ready to begin their record 84 days in space. A cloud-covered Earth lies below. On the distant horizon curves the thin band of atmosphere that is blue sky for those below. The color comes from sunlight scattered by molecules of air. Above it is the endless reach of Skylab's black sky.

*Scientist Pilot of Skylab's third manned mission.

of hitherto unknown and interesting features of the Sun.

Once settled onboard Skylab, our daily operation of the ATM began. In both a visual and intellectual sense, it was very similar to the extensive training we had on our ATM simulator in Houston. In a physical sense, however, we were in the world of zero gravity, a constant reminder of the reality of our situation. Mass without weight was gradually accepted as a normal way of life. New habits in living and new methods of work developed: floating replaced walking, levitation replaced falling, and up was any direction that you could convince your mind was up.

While waiting on the dark side of Earth for our first look of the day at the complex and everchanging Sun, we received a briefing from Scientist-Astronaut Bill Lenoir in Mission Control in Houston:

A couple of words here on the Sun. The first is, I've just gotten word from the back room that we presently have an active prominence on the southwest limb. It is out to 0.03 solar radii now and is growing. You may want to be taking a look at that as the Sun comes over the hill. In active region 33 we show a few bright points coming out today in the plage. That may indicate that we're going to get some resurgence of activity there. Based on what we have seen here over the last few days and some speculation, there are obvious connections between active regions 31 and 32, which are up in the northern hemisphere, and 33, which is in the southern hemisphere.

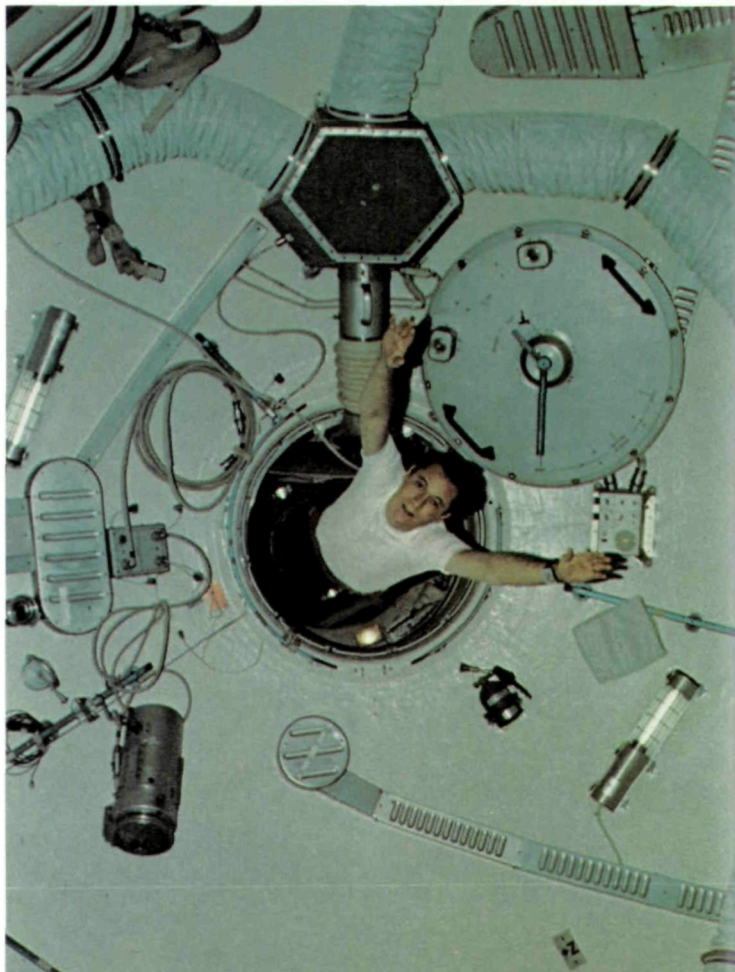
These words were typical of the many interchanges between ground and crew. They were most welcome because they established a rapport that made the observatory's operation much more productive and enjoyable.

The Skylab solar observatory combined the best of many worlds. First, in terms of resolution in space, wavelength, and time, the instruments of the ATM were the most advanced ever put into operation. They could resolve the fine detail of the solar surface much better than those used in previous unmanned satellites; being above Earth's atmosphere, they could observe the Sun in wavelengths that are not visible from Earth; they watched the Sun, particularly the outer corona (the Sun's very faint outer atmosphere, only visible from the ground during fleeting moments of total eclipse) nearly continuously for 9 months.

Second, the controls and displays for the instruments were arranged so that we could use our on-the-spot scientific judgment in managing the experiments. We could watch TV displays of the Sun and the corona as they appeared in ultraviolet light, in X-rays, white light, and in H_α (visible light from hydrogen atoms). We were able to make a good many of the decisions about where to point the instruments and when and how to operate them. The complex and dynamic nature of the Sun, the many and often diverse scientific objectives of each instrument, the limited amount of film available, and even our growing experience meant that a good deal of judgment could be exercised in taking the data. We realized that this provided great leverage for multiplying the efforts of all of the people who had worked on the ATM for many years. We also realized, however, that this exciting opportunity was not without risk. There were also numerous incorrect ways of operating the complex observatory that often required great care to avoid.

Third, our operation of the solar observatory centered around cooperative observing programs that specified just how we should operate each instrument to yield the best data. These programs

THROUGH THE DOOR, headfirst, comes Astronaut Gibson, floating freely from one of Skylab's rooms to another. Room-to-room travel in Skylab's weightless environment was more like swimming than walking, and much more fun.



were planned in great detail many months before Skylab was launched, and we had practiced them on a simulator at our training facilities in Houston. We started out with 26 programs, and others were added during the missions. They proved to be an excellent means of organizing our work so that the observatory was used as efficiently as possible.

The fourth factor that helped make Skylab a particularly powerful observatory was our close contact with a well-informed ground-support team—we were not just a lonely island in the sky. Each day scientists responsible for each instrument developed and sent to us on our teleprinter an operating plan for the ATM—a minute-by-minute program for the daylight parts of each orbit. They also sent general information on the changing characteristics of the Sun, gathered by the National Oceanic and Atmospheric Administration (NOAA) facility in Houston. This plan provided us with a good starting point, and we usually followed it unless we judged that the changing conditions on the Sun made other plans more productive. Houston routinely received data from many observatories as well as from other operating satellites. Some of the data from the ATM television displays and the telemetry from a nonphotographic instrument was assembled in Houston for "quick looks" so that solar scientists there could update the observing plan every day and send us more specific information for each of the instruments.

Fifth, in the same way that we in our orbiting observatory were in constant contact with the ground, the whole Skylab team was always in touch with other working solar astronomers throughout the world. Nearly 150 scientists in 17 countries were daily made aware of our planned observations. Some were notified on an hourly basis of changes in the schedule. These scientists then sometimes coordinated their own observations with ours so that more complete sets of data were obtained on many solar features.

In the planning stages we wondered sometimes whether such an intricate worldwide network could respond quickly to sudden changes on the Sun. Because of its size, would this network be slow to react? Let's take a look at some specific events.

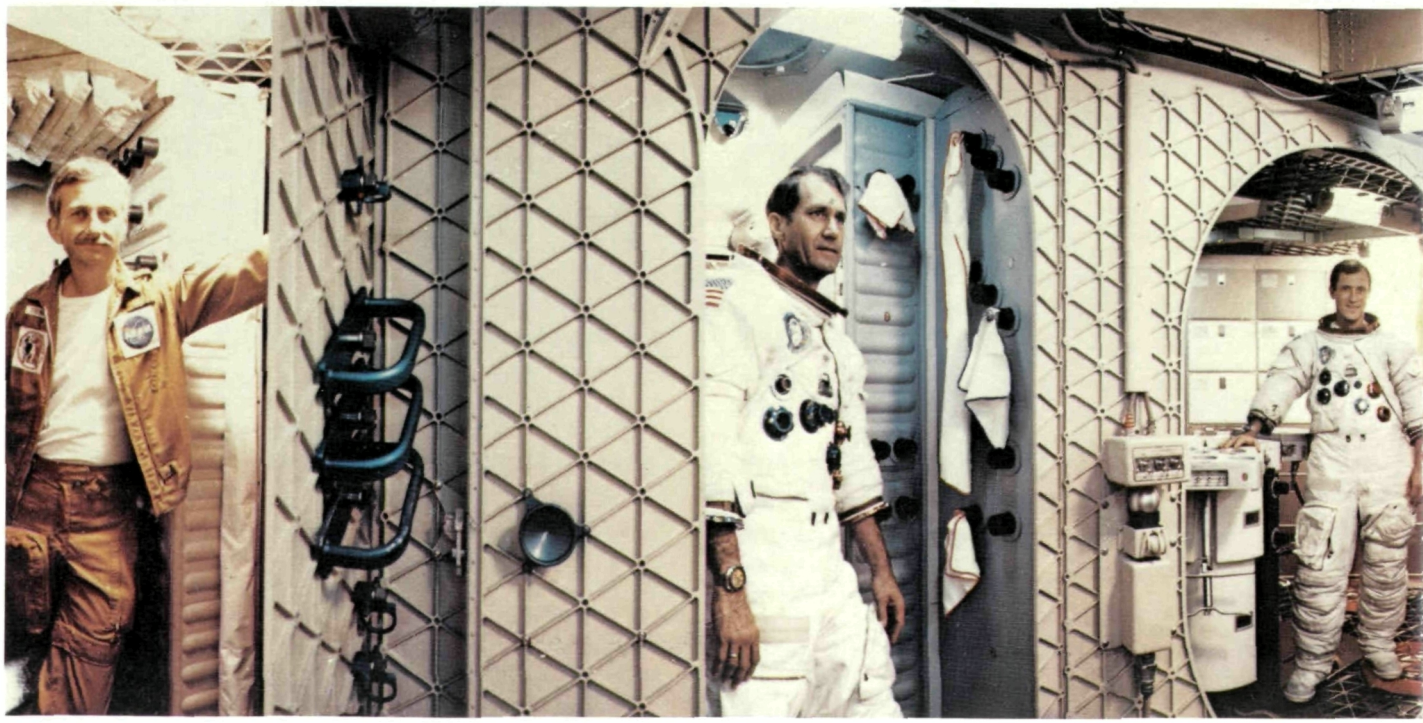
On January 17, 1974, while I was looking at some very hot spots in an active region, a call came from Houston saying that the observatory at Mauna Loa, Hawaii, had just seen a large prominence, a spectacular cloud of dense gas, lifting off

IN SHIRTSLEEVES, Gibson operates Skylab's solar telescope array from the control console in the multiple docking adapter. One hand grips the table to keep him from floating away; he needs no chair. At lower left an unused electrical connector floats freely in Skylab's weightless environment.

the surface of the Sun. Houston recommended one of our planned programs of observing "coronal transients." I started into this new observing program and became excited as I got my first look at the prominence speeding outward through the corona. It was compact, exceptionally brilliant, and quite unlike any coronal structure we had seen before. Fascinated, and with an overwhelming sense of awe, I watched this new feature grow. In less than an hour it was several hundred times as large as Earth, and still moving outward toward the planets. Not until we had slipped into Earth's shadow, and could no longer see it, did I realize how quickly the total ATM team had reacted: Mauna Loa observatory had rapidly contacted NOAA in Houston, and they had immediately relayed the news to the scientist on duty in the ATM support room. He had requested through the ATM representative in Mission Control that we observe the prominence. The Flight Director had approved the request, and it was radioed to us as soon as we came into contact with the tracking facility at Goldstone, Calif. It was only a matter of 9 or 10 min. between the Mauna Loa sighting and the start of our observations.

Four days later, on January 21—less than 3 weeks before our mission would be over—I was at the ATM console watching a moderately active Sun. One active region in particular was very hot, and sporadically releasing small but brilliant bursts of radiation called subflares. By now continuous monitoring of our console displays had allowed us

SKYLAB was the modernistic home for three astronaut crews. A multiple docking adapter was attached to the end of the workshop, and to it was fixed the solar telescope array called the Apollo Telescope Mount. Finally assembled, it made up an orbital laboratory 36 m long and weighing, on Earth, about 91 Mg.



Some Facts About Skylab

Skylab 1

Launch date	May 14, 1973
Launch site	Cape Kennedy
Total manned operational time	171 days
Total operational time (manned and unmanned)	251 days
Date to reenter Earth's atmosphere (estimated)	1980/1981
Overall length	36 m
Overall weight	about 91 000 kg
Length of orbital workshop	8.2 m
Diameter of orbital workshop	6.7 m
Orbit altitude (average)	435 km
Orbital velocity	8 km/s
Period to circle Earth	93 min
Earth orbits completed during operational time	3900

Astronaut crews

Skylab 2—first manned mission (May 25 to June 21, 1973): 28 days

Charles Conrad, USN
Joseph Kerwin, M.D., USN
Paul J. Weitz, USN

Skylab 3—second manned mission (July 28 to Sept. 24, 1973): 59 days

Alan L. Bean, USN
Owen K. Garriott, Ph. D.
Jack R. Lousma, USMC

Skylab 4—third manned mission (Nov. 16, 1973, to Feb. 8, 1974): 84 days

Gerald P. Carr, USMC
Edward G. Gibson, Ph. D.
William R. Pogue, USAF

First manned mission backup crew:

Russel L. Schweickart
Bruce McCandless II, USN
Story Musgrave, M.D.

Second and third manned mission backup crew:

Vance D. Brand
Don L. Lind, Ph. D.
William B. Lenoir, Ph. D.

THE NINE ASTRONAUTS of the three Skylab crews posed for this postflight portrait in a training simulator at the NASA Johnson Space Center near Houston, Tex. This unique 360° view, made by photographer Michael Lawton for the *National Geographic Magazine,* shows the bottom floor of the four-story living space where these men lived and worked for a total of 171 days during the Skylab mission. Bean, Lousma, Conrad, Weitz, Kerwin, and Carr stand in the experiment compartment where medical tests and physical conditioning were performed; Gibson stands in the ward room (kitchen-dining room); Pogue at the door of the waste management compartment (bath); and Garriott in the sleep compartment (bedroom).

to develop a feel for the Sun's level of activity—in a sense, to take its pulse. We had been disappointed that neither our crew nor either of the previous crews had managed to observe the very beginning of a flare, a short-lived explosion on the Sun's surface.

We hoped that by observing a flare's birth we could find keys to the mechanism by which the Sun releases great quantities of energy from a very small volume in a fraction of a minute. But every time we realized that a flare was taking place, and started the instruments, we were too late to observe the initial energy release.

Owen Garriott, Scientist Pilot of the previous Skylab mission, had suggested that when a tiny bright point appears on the extreme ultraviolet image of the Sun, it may be an early signal that a flare is beginning. So, as the active region shown on my TV display seethed with small energy fluctuations, I practiced the exact control panel procedures I would use if a flare erupted. (I had done this many times before, but to no avail.)

Suddenly, a small bright point appeared right in the center of my screen. As I started the instruments taking data rapidly in their flare modes, I was elated to see the bright point blossom into a full-blown flare.

My most interesting and challenging day on Skylab was January 26, 1974, when Houston asked me to develop and implement most of the plans for one full day's observations. They did this as an experiment, to see how an orbital observatory could be run on future NASA Space Shuttle missions when experimenters themselves will fly. Using the teleprinter, they sent up a general statement about the scientific goals and limitations of each experimenter and their knowledge of the state of the Sun. The rest was left to me.

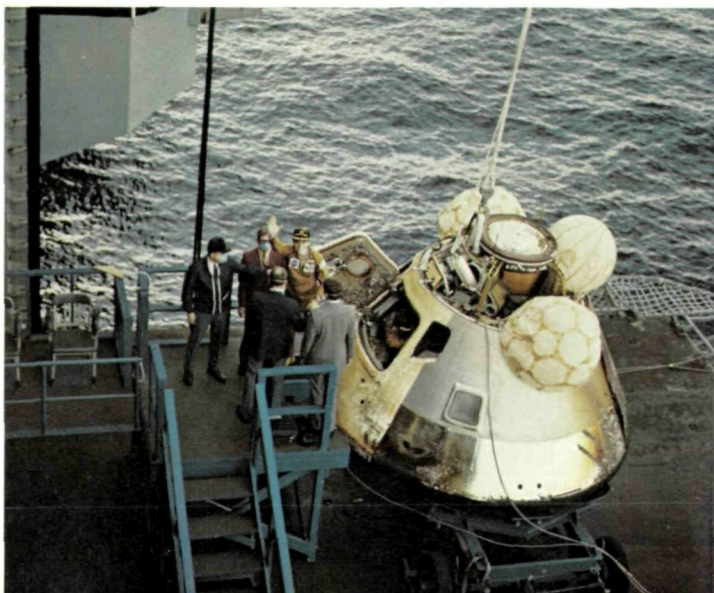
I had a fascinating day, completely involved, entirely committed. Laying out the schedule was relatively straightforward. Routine data-gathering formed the framework that filled in with observations of the Sun's most interesting features. Knowing the experiments' objectives, the degree to which they had already been met, and the current state of the Sun, I could do all the short-term planning and make all the real-time changes in the observing program that were required. By now the matching of scientific objectives with the operation of the console had become second nature and the ATM could be played like a piano, by ear, with cumbersome sheet music put away. On the other hand, this day's work also demonstrated the importance of an even closer link than we had between ground scientists and in-flight observers. I found that I sometimes missed the wisdom of the ground personnel in forming my decisions. Two heads are certainly better than one, especially if they can exchange knowledge freely.

The ATM contributed a staggering quantity of new data on the Sun. It also showed us how to use man to greatest advantage on long-duration space missions.

We realized this during our 84 days in flight, as we assumed many roles: observers, doctors, scientists, space pilots, cooks, housekeepers, space walkers, and technicians. In filling these roles we recognized that man makes his best contributions and is in his best psychological health when his tasks let him be creative and intellectually challenged. As our mission ended, we were still becoming more and more proficient, and we were still increasingly interested in what we were doing. Skylab demonstrated the value, to us and to the scientific world, of giving the onboard observer a high degree of freedom, letting him lend his mind and his creative abilities to the tasks at hand. We left Skylab with the first-hand knowledge of how to plan the operation of the space station of the future, perhaps a permanent national or international facility.

Significant dividends will result from heavy reli-

HOME AT LAST, after a record stay in orbit, Gibson steps to the deck of the U.S. aircraft carrier *Wasp*. Still inside are Carr and Pogue and a heavy cargo of precious film. Their trusty command module, scorched by air friction on reentry into the atmosphere, was the same that had carried them to Skylab nearly 3 months before. For 84 days it was parked outside Skylab's door, waiting for the trip back home.



A THOUSAND SUNS dot the sky between us and this distant galaxy, where uncounted more blur together in a spiral pattern that is much like our own galaxy, the Milky Way. Two smaller satellite galaxies appear as circular and elliptical shapes in this long exposure photograph. The nearby stars seen here as dots are a part of our own spiral galaxy. The Andromeda Galaxy, our closest extragalactic neighbor, is about 2 million light years away and contains about 100 billion suns.

ance on the judgment of the observer inside a science or technology laboratory, another solar observatory, or an Earth observatory.

This volume presents the highlights of the new and exciting picture of the Sun that has come from Skylab. Turning the vast amount of data into knowledge has really just begun, and will continue for many years. Behind the data lie the mechanical and scientific complexity of Skylab, the people and resources that made it a success, and the many years of planning.

Although Skylab was not as visible and dramatic, perhaps, as our first lunar landing, I hope that as you read you will share with me the feeling that it was an exciting, meaningful, and most productive step in our exploration of the universe.

1
The Nearest Star

It is true that from the highest point of view the Sun is only one of a multitude—a single star among millions—thousands of which, most likely, exceed him in brightness, magnitude, and power. He is only a private in the host of heaven. But he alone, among the countless myriads, is near enough to affect terrestrial affairs in any sensible degree; and his influence upon them is such that it is hard to find the word to name it; it is more than mere control and dominance.

—Charles A. Young, 1896

Our universe is unbounded and limitless, consisting of uncounted billions of stars burning in the dark, unmeasured span of space. On and on it goes—a reach of space and time that seems more than mind can grasp. Among the stars and nebulas, among the many galaxies and clusters of galaxies whirls the spiral galaxy of which we are a part. We see it from within as a faint blur of distant stars that arches in a milky streak across the nighttime sky.

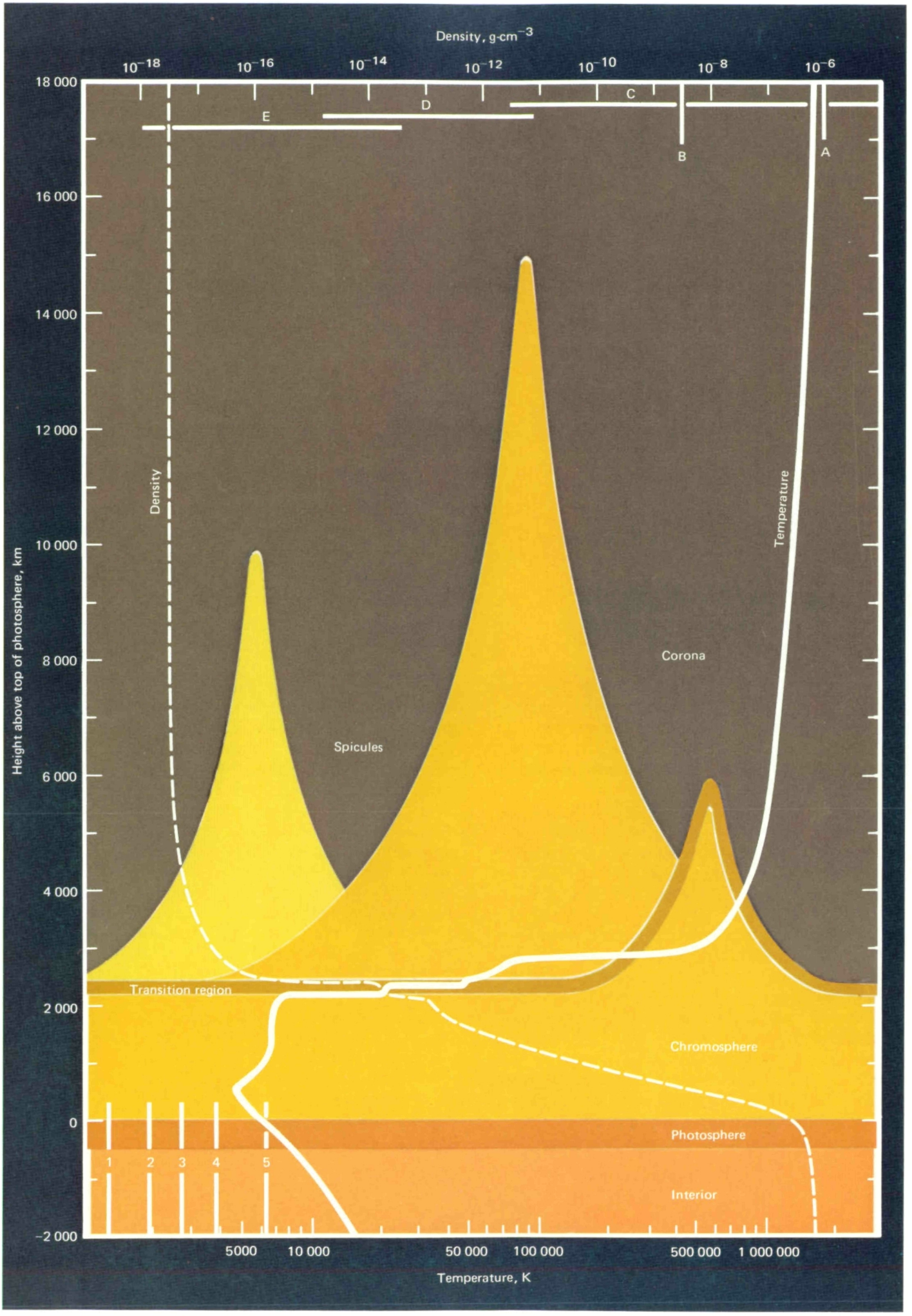
To us this single galaxy, our Milky Way, seems incomprehensibly vast—a hundred billion suns sprinkled in a spiral pattern to form a flat, rotating disk. The spiral is so large that a flash of light from one edge must race a hundred thousand years to reach the other side.

Far out along one spiral arm there gleams the star we call our Sun. It is, we think, an average star of middle age and middle size, much like hundreds of thousands of its distant neighbors. It belongs to a common class of stars called dwarfs, to distinguish them from giant red stars like Antares and Betelgeuse, whose diameters would stretch across 500 suns. The diameter of our Sun is about 1.4 million km, nearly 10 times that of the largest planet, Jupiter, and 100 times that of Earth.

Our small Sun may be unique in one respect: its family of planets; however, they too, may be common features of the universe. We are much too far from other stars to determine directly whether any has Earths or moons or Jupiters.

Like all planets, Earth derives its light and heat from the Sun. It is sometimes surprising to realize how far we are from the Sun; in its warm rays we feel much closer to our star than facts of distance say we are. The Earth travels around the Sun in a nearly circular orbit, never getting closer than about 140 million km, more than 400 times the distance between Earth and Moon—man's furthest excursion into space. A spacecraft sent to the Sun would spend several years en route. Were it possible to fly to the Sun in a jet airliner, it would take nearly 18 years to make the trip at 1000 km/hr.

The Sun has no permanent features and is entirely gaseous—a glowing ball of chiefly incandescent hydrogen. Other elements, all in gaseous state, are present in amounts that seem to fit a universal, cosmic recipe: about 10 parts hydrogen to 1 part helium, with a pinch of each other element from the periodic table, but mostly oxygen, carbon, nitrogen, magnesium, and iron. Although we speak of the "surface" of the Sun, and of specific layers in its atmosphere, the Sun is really all atmosphere. It has no easily defined boundaries or sharp discon-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Spicules
Corona
Transition region
Chromosphere
Photosphere
Interior
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−2 000
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50 000
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1 000 000
Temperature, K

TEMPERATURE AND DENSITY vary with height in the Sun's atmosphere according to these curves. Height in kilometers is shown increasing upward on the scale at left, measured from the top of the photosphere where sunspots are seen. Yellow and orange peaks are chromospheric spicules that jut up into the corona; the transition region between chromosphere and corona is shown as a dark yellow band, only a few hundred kilometers thick, which follows the spicule outlines.

At the top of the photosphere (zero height) the solar temperature is about 6000 K; below this, in unseen layers of the solar interior, the temperature increases as the center of the Sun is approached. Temperature continues to fall above the photosphere until a sharp minimum occurs in the low chromosphere. The temperature of the solar atmosphere then begins to rise, slowly in the upper chromosphere, and then rapidly, in steps, through the thin transition region. At a height of about 5000 km above the photosphere, in the corona, a temperature of 10^6 K and more is reached. Numbered temperature lines at lower left show familiar laboratory temperatures such as (1) temperature at which gold melts, 1337 K; (2) melting point of iron, 1808 K; (3) boiling point of silver, 2485 K; (4) temperature of acetylene welding flame; and (5) iron welding arc. Higher temperatures to right of (5), which characterize most of the solar atmosphere, are seldom achieved in our terrestrial experience. Density of the gaseous solar atmosphere falls rapidly with height above the photosphere. (See the scale at top, expressed in grams per cubic centimeter.) Between the photosphere and the top of the transition region, in a range of less than 3000 km in height, density falls through 10 orders of magnitude. Even in the relatively dense photosphere, the solar gas is so thin that it would be considered a vacuum on Earth. Lettered lines at top give terrestrial densities such as (*A*) density of our atmosphere at an altitude of 50 km; (*B*) Earth atmosphere at 90 km; (*C, D, E*) ranges of vacuum densities achieved by laboratory vacuum pumps: (*C*) mechanical vacuum pump, (*D*) diffusion pump, and (*E*) ion pump.

tinuities like those on Earth that separate air and water and solid ground. The solar corona, chromosphere, and photosphere are distended, rarified regions that blur into each other and have definite form only when seen at great distance, as from Earth. The average density of the Sun, about 1.4 g/cm^3, is only about a quarter of that of Earth. The solar photosphere which we see with the naked eye is so diffuse and thin that we would call it vacuum here on Earth, and the layers above it, the chromosphere and corona, are far less dense. The Sun becomes gradually denser as we go inward, but it is not until we have gone a tenth of the way to the center that we find material as dense as the air we breathe on Earth, and not until we are halfway to the center that the Sun is as dense as water.

No one has seen within the Sun. We presume the central temperature is about 15 million kelvins and the central density is about 160 g/cm^3, or 10 times that of ordinary metals. These estimates are based on calculations that depend upon our knowledge of the surface temperature and pressure, the mass and size of the Sun, and the physical laws that govern stellar interiors.

The exceedingly high temperatures and densities of the solar interior trigger nuclear reactions that produce the energy that fuels the solar furnace. The exact nuclear process is not known, but the most likely is one by which hydrogen, the Sun's most abundant fuel, is converted to helium. In this process of nuclear fusion, energy is released. In the highly compressed solar interior, the disruptive forces of nuclear reactions are contained and muffled by a press of gravity that is 250 billion times as great as that on Earth.

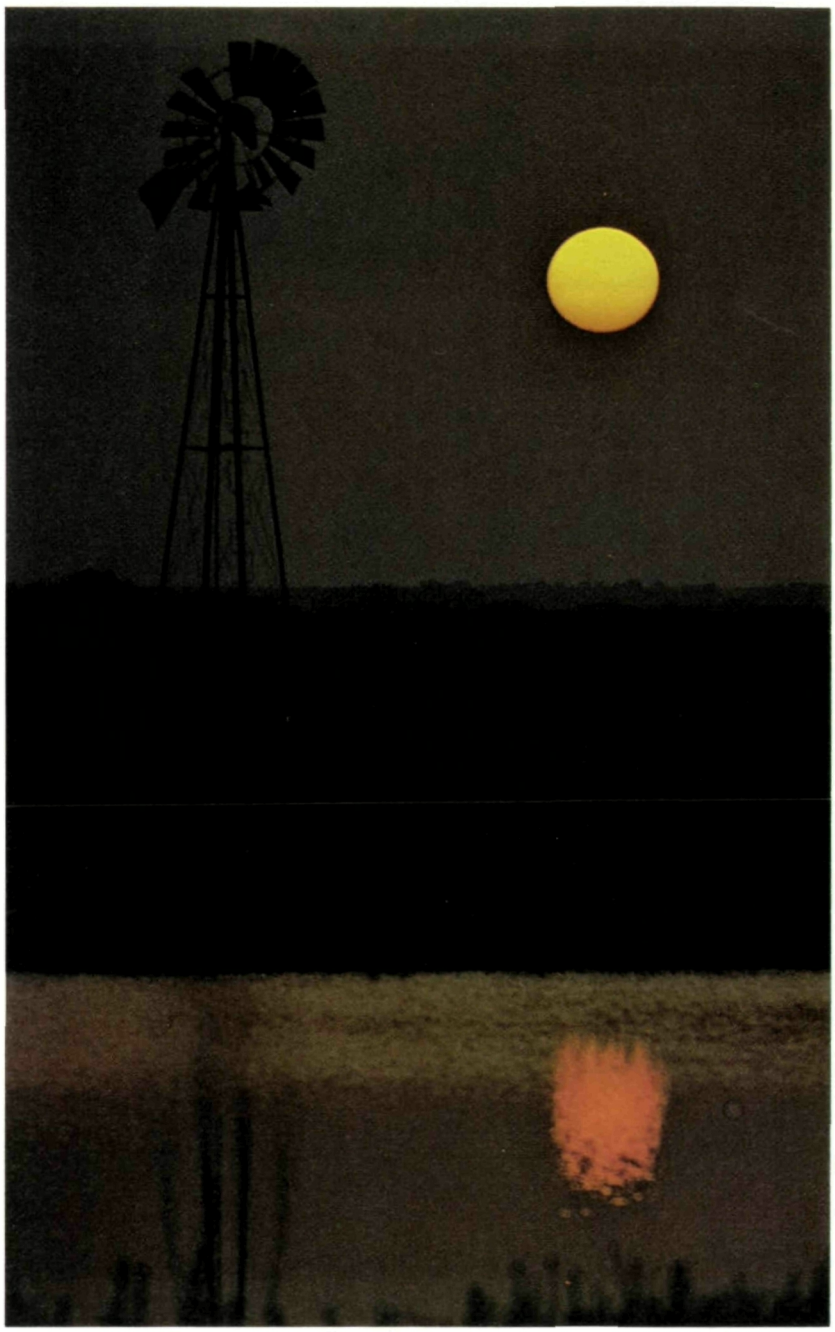
For each helium atom created in this way, a small amount of energy is emitted in the form of a gamma ray at the invisible, short-wavelength end of the electromagnetic spectrum. The normally piercing gamma rays travel but a short distance through the densely packed material at the center of the Sun before they are absorbed and then reemitted to be absorbed again. The nuclear energy carried in gamma rays finds its way outward through the Sun by a long and tortuous series of repeated absorptions and reemissions, gradually losing energy and changing to longer and longer wavelengths in the process.

When the energy finally reaches the surface of the Sun, most of the gamma rays have been replaced, first by X-rays and then by ultraviolet rays, so that when they at last emerge, they are in the form of the visible and infrared radiation that makes up the sunshine that we feel on Earth. It is a measure of the size and density of the solar core that energy created by nuclear fusion at the center of the Sun takes nearly 50 million years to jostle its way to the surface. There the solar energy easily escapes to space, traveling at the speed of light to reach the orbit of the Earth in but 8 minutes.

The temperature of the Sun decreases outward from the core, and at the visible surface of the photosphere it has fallen to about 6000 K. This white-hot surface radiates energy at a rate of about 3.8×10^{23} kW, which flows out equally in all directions. Earth—a tiny target at a great distance—intercepts but a billionth part of the prodigious solar output of heat and light. But even this small share deposits on Earth a continuous supply

of about 8×10^{14} kW, which is vastly more than the full capacity of all the power plants ever envisioned on Earth. Each square meter of Earth receives about 1.5 kW of solar energy, which, if harnessed efficiently, could heat and light a small room.

In producing this energy, the Sun's nuclear furnace consumes about 5×10^9 kg of hydrogen each passing second, burning outward in successive shells and gradually transforming the solar interior to a predominantly helium core. We estimate that hydrogen within the Sun has been consumed at this fantastic rate for the past 4 or 5 billion years. Yet the Sun is so large that there is still hydrogen within it to continue the process at the present rate for another 100 billion years, or 20 times as long as it has burned in the past. Long before the hydrogen is depleted, however, helium will probably begin to serve as fuel, in other fusion reactions to create other elements, which will later take their turn as solar fuel.



The Sun: Ruler, Fire, Light and Life of the Planetary System was Richard Proctor's title for his book on solar physics written in 1871. Indeed, all life on Earth depends upon the Sun. "Solar energy," which we talk about today as new, has served Earth with constancy for about 5 billion years.

The Sun is the ultimate source of almost all the energy we use, because wood, coal, and oil are fossil fuels that store the energy of sunlight from eons past, and in harnessing wind and river we are but harvesting the solar heat that drives the circulation of the air and lifts the moisture from the sea. Our food supply is totally dependent on the Sun, directly or indirectly, through solar photosynthesis in green plants and aquatic forms. Photosynthesis also releases to the atmosphere the oxygen essential to all animal life.

The same sunlight that feeds and gives us fuel and oxygen warms us as well. Without it the salty seas would freeze and the very atmosphere would condense and solidify. Without the Sun there would be no rain, no snow, no rivers or lakes, no winds or clouds or blue of the sky, no rainbow, no moonlight, and no vestige of life upon our planet. Little wonder that early man on every continent recognized his total dependence on the solar star and fell to worship it.

Gradually the early worship of the Sun grew into a more practical desire to know and understand it. Was it, as the Greek Anaxagoras said, a mass of fiery stone, 56 km across? Or, as dictated by medieval dogma, a perfect fire? How far away was it? How large? How hot? How constant? How long would it last? What were the spots seen repeatedly on its surface by Chinese astronomers 200 years before Christ, and by Galileo with a telescope

in 1611? Were there changes on the Sun that might explain the cyclic change of weather and climate on Earth? The ice ages? The recurrent droughts and their implications for world concerns of the 1970's?

Today, about 20 percent of the world's astronomers, including over 200 in the United States alone, are engaged in the full-time study of the Sun. They work in universities, observatories, in Government laboratories, and in private industry. A large number of amateurs make solar astronomy their specialty.

The Sun is studied by astrophysicists as a star—the only one that can be seen in detail. It is studied by physicists as a laboratory where unique conditions of temperature, density, fluid motions, and magnetic fields exist. It is studied by atmospheric physicists, aeronomers, and climatologists for its important terrestrial effects.

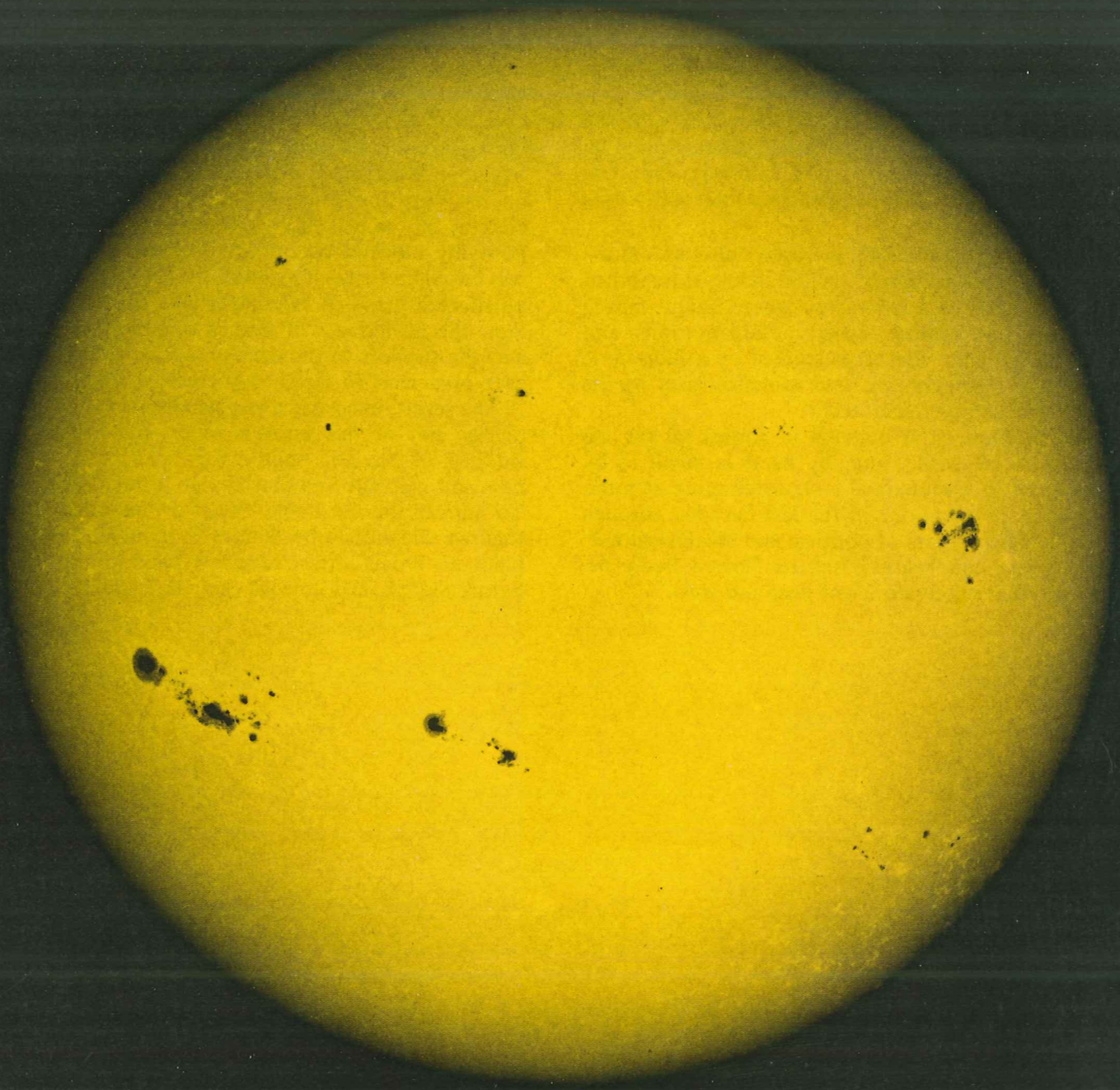
Solar research is pursued in almost all the nations of the world, and, by need as much as by tradition, it has enjoyed a vigorous spirit of international cooperation. In the last decades, through the coldest winters of political and idealogical war, solar data and research results flowed freely between solar observatories of East and West.

In these traditions Skylab gave much of its budget of time and resources to an intensive, cooperative study of our Sun, to achieve what now seems to be the greatest step ever made in the long history of man's study of the Sun.

Observations of the Sun from Skylab have changed the course of modern solar physics and have built a lasting bank of solar data that will long serve astronomers of all the world. The power of Skylab was its ability to keep a continuous watch on the Sun simultaneously in all wavelengths, including the crucial ultraviolet and X-ray radiation normally blocked by our atmosphere. This power was brought to bear by the force of the most sophisticated array of telescopes ever turned on the Sun, the advantages of trained observers in space, and the support of the most extensive world effort ever organized to wrest the secrets from the Sun.

The results exceeded all expectations.

The aim of this book is to explain the major findings of Skylab's solar effort, and to show the new and colorful Sun that Skylab brought to view. To answer the inevitable "What do we know now that we did not know before?" we must first explain, in broad terms, what we knew of the Sun before Skylab, and how we came to know it.



SUNSPOTS are revealed when the Sun is seen with an ordinary telescope. They are darker than the surrounding photosphere because they are cooler—about 4200 K as compared with 6000 K. Sunspots can be seen with the naked eye under favorable conditions and have been observed for thousands of years. Their details were discovered by Galileo and others who looked at them with the first telescopes in the early 17th century.

2
The Masks of the Sun

When an observer, provided with suitable telescopic appliances, examines the surface of the sun, he finds a most interesting field before him. At first view, indeed, it is less impressive than the moon; there is not so much to attract the immediate attention—no mountain-ranges and craters, no shadows, rills, or rays. But, if the telescope is a good one and the atmospheric conditions favorable, the details soon begin to come out.

—Charles A. Young, 1896

The story of what we know of the Sun is also the history of solar instruments: the telescope, spectroscope, and many others. Without them we would know little more of the Sun than its position in the sky. Indeed, man's understanding of the Sun has never proceeded regularly, but always in surges, following new instrumental breakthroughs. Each new look, from Galileo's simple telescope to Skylab's powerful array, has brought a new and often surprising view of what was once thought to be a simple sphere of fire. Each new look has shown the Sun to be more active and more complex. In many cases, new ways of looking have revealed new and previously hidden faces of the Sun, for the Sun's appearance changes dramatically from layer to layer, as though it wore mask on mask.

THE SUN IN WHITE LIGHT

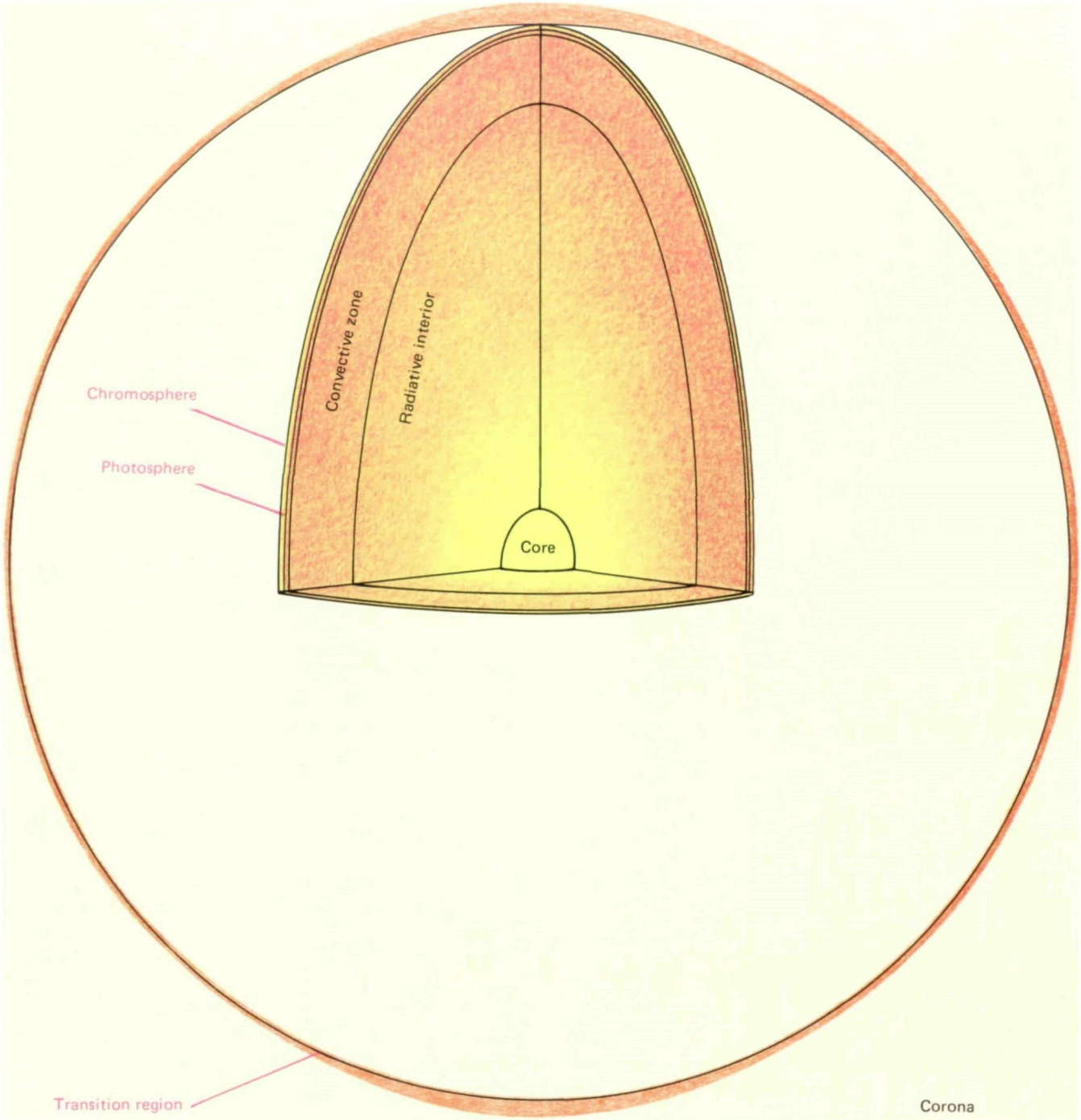
The Photosphere

The mask most commonly seen, and the first to be studied in detail, is the Sun's white light face: the layer in which sunspots are seen, and which astronomy calls the sphere of light or photosphere. It is the white, bright surface we see with the naked eye—the luminous, 6000 K surface that radiates most of the Sun's light and heat to space. To most of us it *is* the Sun.

The photosphere is a very thin layer of the Sun—no more than about 500 km thick, or less than 0.1 percent of the solar radius. We can see no deeper than this thin shell; although gaseous and diffuse, it becomes completely opaque in a relatively short distance, and that is why the edge of the Sun appears sharply defined, and why early astronomers were led to suppose it could be solid or liquid. The photosphere was long thought to be perfectly spherical and without blemish, but in the early years of the 17th century, with the invention of the astronomical telescope, man's eyes were shown the first details of its intricate and changing surface.

Sunspots

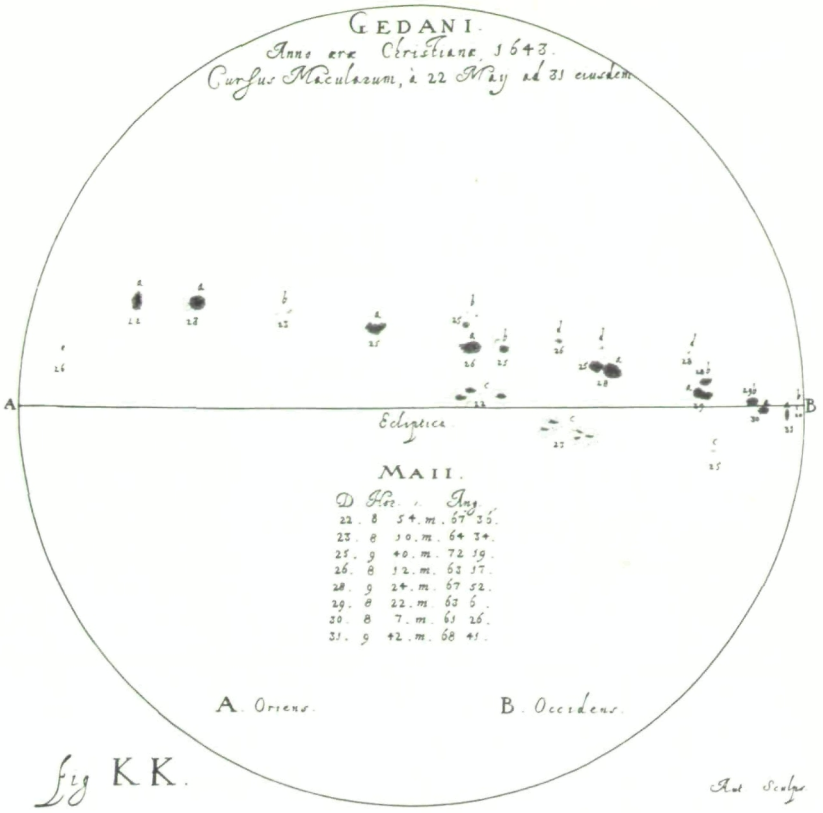
The first and most remarkable features found were sunspots. Dark features on the Sun have been seen and recorded for at least 2000 years. Records from China and the Orient report, on the average, about 5 or 10 sightings per century, which are taken now as evidence of unusually large spots or sunspot groups, because smaller features could not be seen. It is not difficult to see large sunspots with the naked eye if one looks quickly when the



IMAGINARY SLICE cut from the ball of the Sun lets us see all its known and suspected layers. In truth, no one has ever seen beneath the photosphere. The Sun's prodigious energy is believed to be generated by nuclear processes in the deep interior of the Sun, in a dense, hot central *core,* about the size of Jupiter, the largest planet. Core temperature is estimated to be about 15×10^6 K: hot enough to trigger the process of atomic fusion by which hydrogen, the Sun's abundant fuel, is converted to helium. Energy released from this continuing process seeps outward through the dense interior by *radiation*—the same method that carries sunlight through the solar system. Near the solar surface, the outward flow of energy becomes turbulent and unstable, creating giant, rising bubbles of gas that make up the *convective zone.* Finally, in a thin layer called the *photosphere,* the solar energy that has worked its way to the surface at last becomes visible—as the white ball of light we see each day with the naked eye. To escape the Sun the light must still pass through three more layers, each less dense than the ones before: the *chromosphere,* here shown over the full disk of the Sun; the thin *transition region;* and the ethereal, extended *corona,* largest of the many masks of the Sun. Temperature in the Sun is hottest in the core, and decreases slowly to the surface. At the photosphere the solar temperature has dropped to about 6000 K. The temperature reaches a minimum of about 4300 K in the low chromosphere, then rises rapidly to more than 10^6 K in the lower corona. Waves carrying energy upward from the convective zone probably release their energy in the chromosphere, causing the abrupt temperature rise.

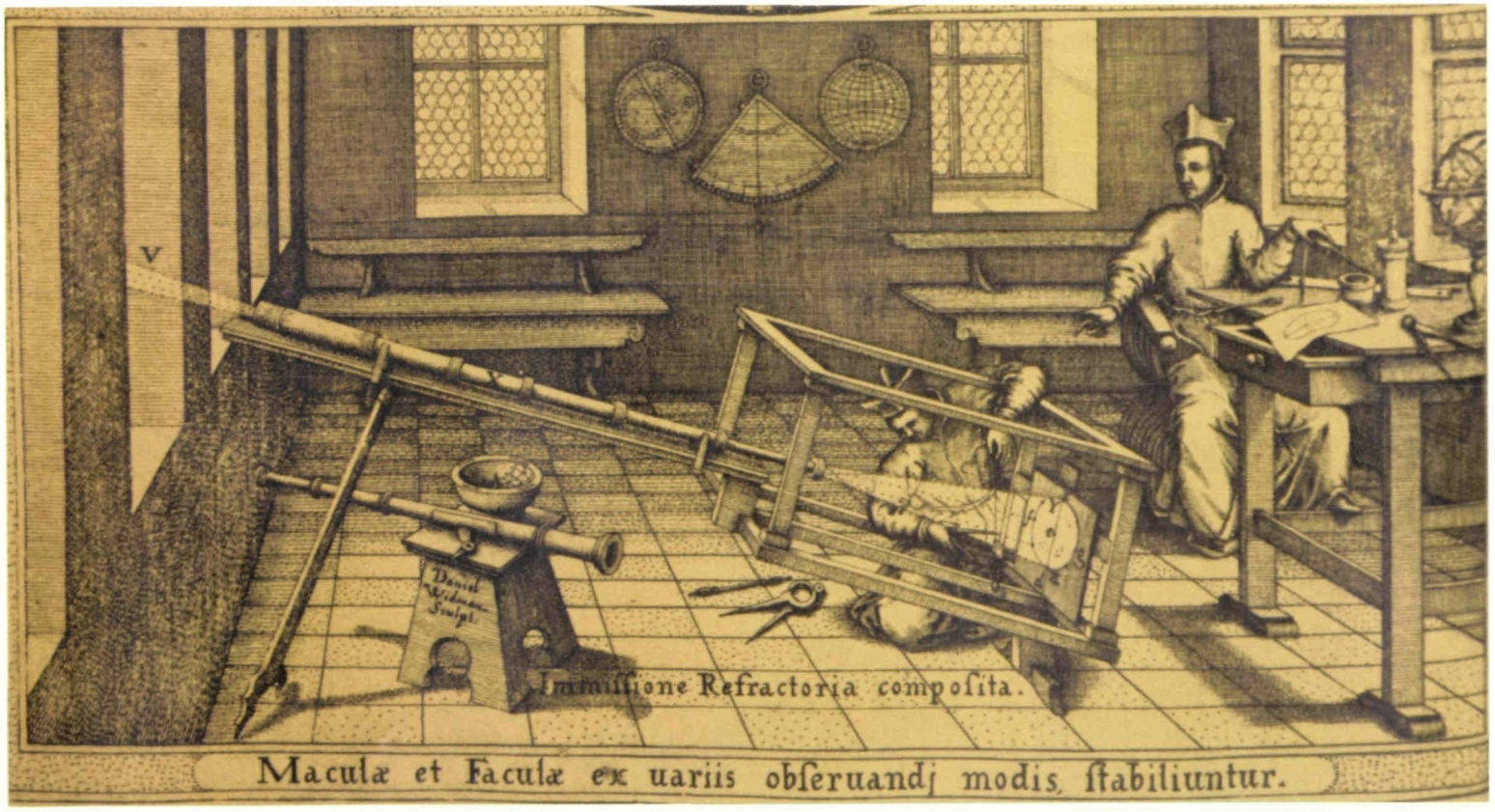
brilliance of the Sun is dulled in setting or in rising, or when it is reddened by heavy smoke or haze. But few, if any, of the early records seem to have associated the spots with the Sun itself, probably because the dark spots were so poorly and intermittently seen. They could be mistaken for dark features floating in our own atmosphere, or planets between Earth and the Sun.

The first telescopes, introduced by Galileo and several other European astronomers in about 1610, did not properly discover sunspots, but rather gave the first clear looks at them. They revealed that the spots were more than dots. Galileo and others demonstrated in careful, published drawings that the spots consist of a dark, central region called the "umbra," meaning "shadow," surrounded by a lighter rim called the "penumbra," or "partial shadow."



SUNSPOT OBSERVATIONS in the 17th century were made much as today. The solar image is projected by a long-focus telescope onto a card, where observers trace the details and positions of individual spots, noting changes and motions. Here Christopher Scheiner and a fellow Jesuit scientist trace sunspots in Italy in about 1625.

AN EARLY DRAWING of the Sun and sunspots by Johannes Hevelius, renowned Polish astronomer of the 17th century. Here Hevelius shows the path and changes in sunspots that crossed the disk of the Sun between May 22 and May 31 in 1643 as they were seen in Danzig.



Better telescopes showed sunspots in better detail. The sunspots are usually irregular in shape, some large and some small, and they most often appear in groups, frequently with two principal spots per group. Penumbras are made up of filaments that stream outward from the central umbra in radial fashion. Individual sunspots persist from several days to as long as several months, generally increasing in size and complexity before finally fading away.

Once the spots were shown to be a part of the Sun, scientists used them to demonstrate that the Sun rotated, by watching and measuring their apparent drift across the face of the Sun from day to day.

The Sun rotates in about 27 days. It does not rotate like a rigid ball; the Sun's atmosphere spins faster at the equator than near its poles, introducing a kind of atmospheric slippage or shear known as "differential rotation."

But what were these dark spots in the photosphere?

Most early astronomers believed them to be clouds drifting over an undisturbed and still comfortably perfect solar surface. In 1801, Sir William Herschel, discoverer of the planet Uranus and the leading astronomer of his day, published a different view. Sunspots, Herschel said, were not clouds but holes in clouds. The white photosphere, in his opinion, was an incandescent cloud layer that covered a darker, cooler layer below; sunspots offered occasional views of this lower surface, which, Herschel felt,

> . . . is most probably also inhabited, like the rest of the planets, by beings whose organs are adapted to the peculiar circumstances of that vast globe.

Other explanations of the 19th century attributed sunspots to storms, to bubbles on a liquid Sun, splash marks of meteor impacts or of debris thrown out by solar eruptions, mountains poking through the clouds, or solid slag on a white-hot, molten surface.

These fanciful theories of but a century ago are of interest because they reveal the limitations of astronomy without physics: of pictures and visual observations without the benefit of accompanying measurements and deductions of physical quantities, such as temperature, density, velocity, and chemical composition.

The use of physical methods in astronomy, now called astrophysics, began in earnest in the latter

THIS REMARKABLY DETAILED DRAWING of a single sunspot was made by the eminent American scientist Samuel Langley, in the cold, clear air of Pittsburgh, just before Christmas in 1873. Langley later became the Secretary (Director) of the Smithsonian Institution in Washington, D.C., and in the early 1900's was a pioneer in aviation. Photographs made in modern times confirm much of the detail captured by early visual observers such as Langley, who spent long hours at their telescopes to catch moments of unusual sky clarity.

part of the 19th century, with the use of the spectroscope. This device, which we will soon describe, was the second of the instrumental breakthroughs that released an avalanche of new knowledge of the Sun.

The first studies of the spectrum of light from sunspots, using a spectroscope, showed that they were cooler by about 30 percent than the surrounding photosphere. A typical temperature for the darkest and coolest part of a sunspot is about 4300 K, which is still hotter than an acetylene welding flame. The photosphere, in contrast, is about the temperature of an electric welding arc.

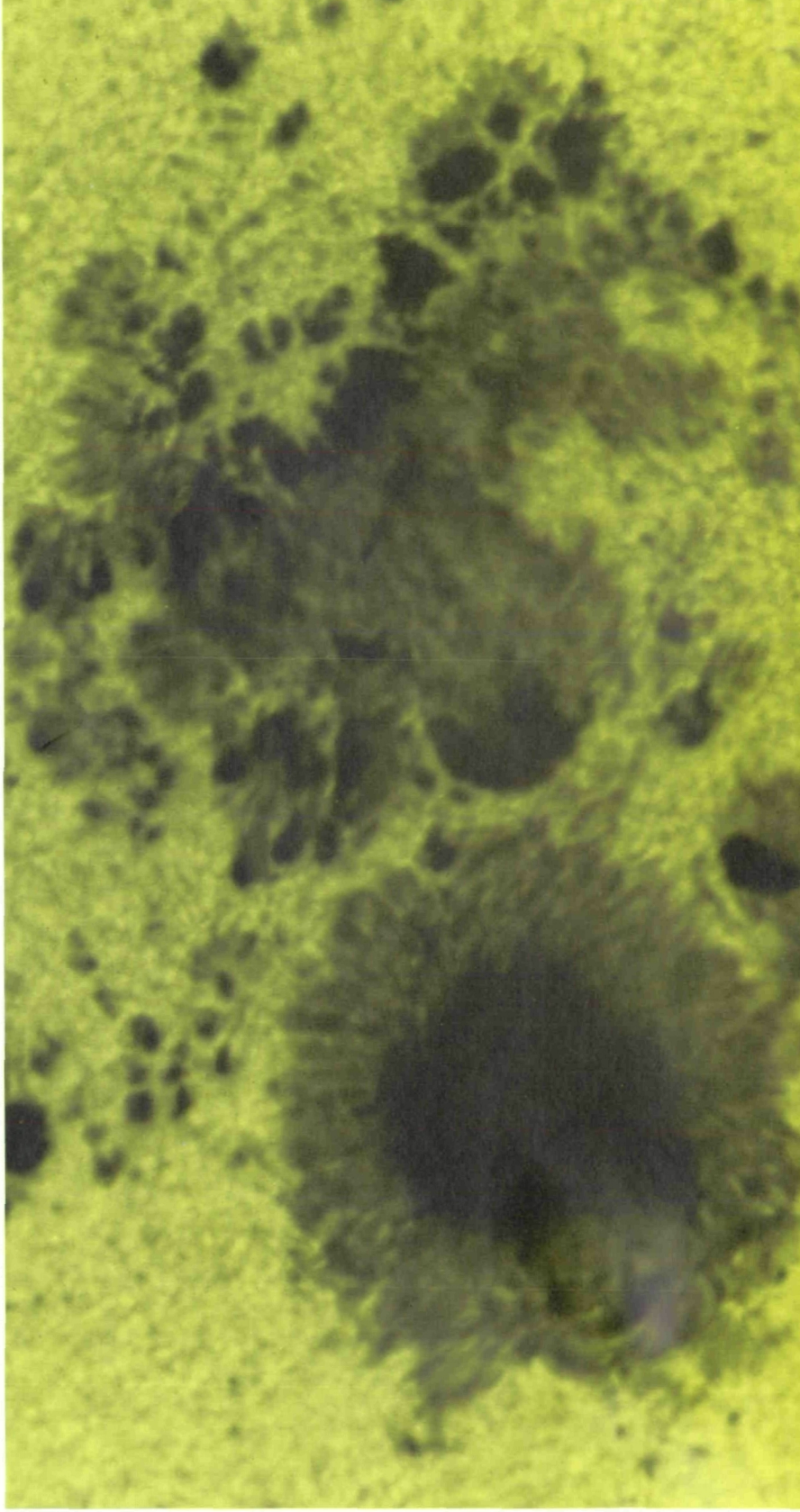
The spectroscope also revealed that material in sunspots flowed generally upward and outward from the umbra, along the penumbral filaments, suggesting that sunspots were seats of strong, circulatory motion, perhaps like terrestrial tornadoes. If sunspots were solar storms, as many then supposed, they were gigantic and persistent by terrestrial standards. Many of the spots observed were as large as Earth, and some were 10 times larger—the size of Jupiter. They also were longer lasting than terrestrial storms.

An adaptation of the spectroscope by George Hale of the Mt. Wilson Observatory in the early years of this century provided the real key to the understanding of sunspots. Hale found that within sunspots were magnetic fields of such enormous strengths that they dominated all material in their vicinity. This provided an explanation for almost all the observed features of sunspots: their cooler temperatures (magnetic fields inhibited the normal flow of heat toward the surface), the arched penumbral filaments (matter arranged on magnetic lines of force), the frequent occurrence of spots in pairs (of opposite magnetic polarity), and their long persistence.

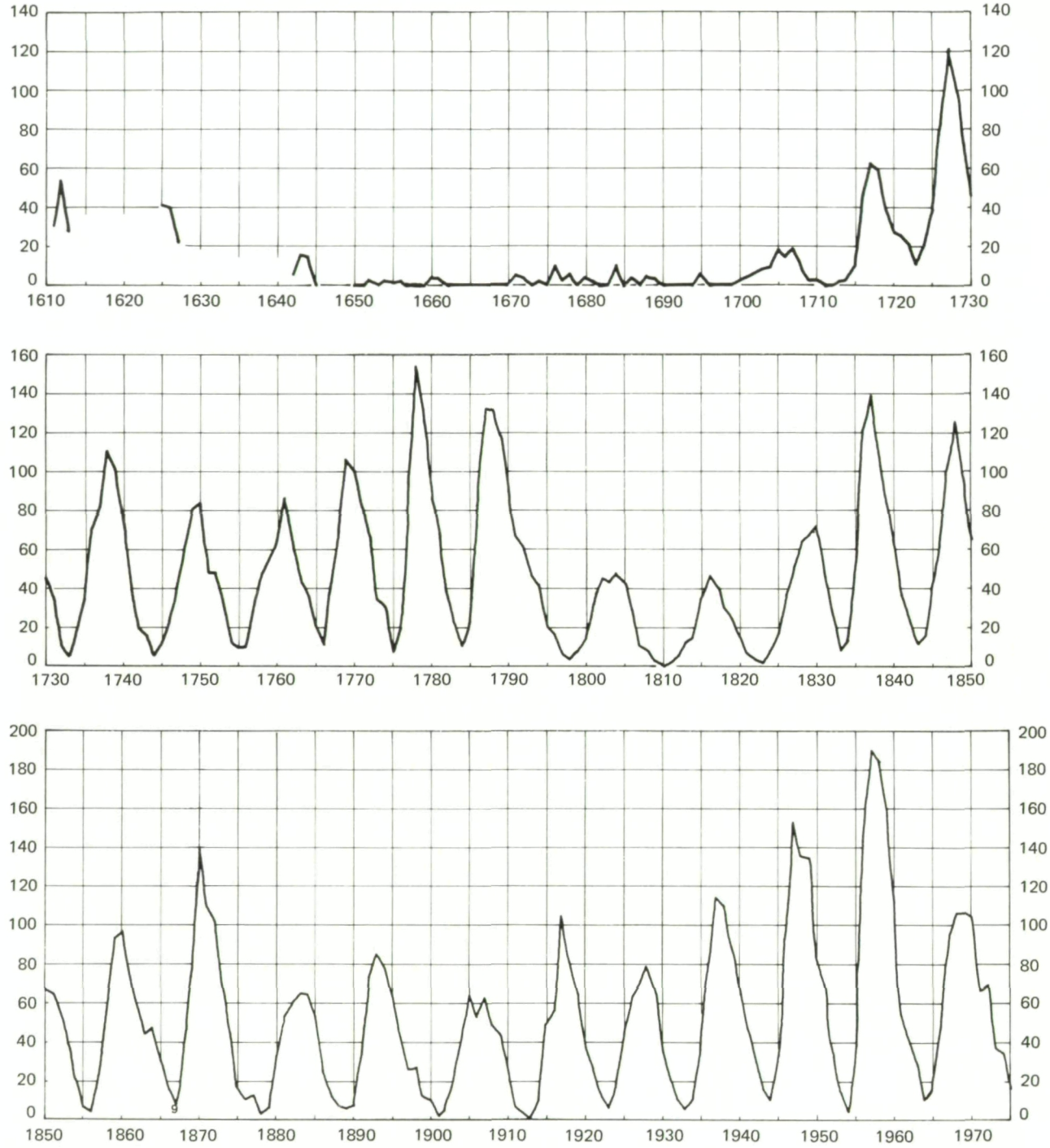
The Sunspot Cycle

Sunspots, to many, are best known in connection with the sunspot cycle: the regular pattern in the number of spots that appear on the Sun from year to year.

Continuous observation for more than two centuries has established that sunspots reach a maximum number every 11.2 years, on the average. Between times of maxima, their number falls to a well-defined minimum. At the time of maximum in the sunspot cycle we may find 100 or more spots on the visible hemisphere of the Sun at one time;



A MODERN PHOTOGRAPH of sunspots taken at the Sacramento Peak Solar Observatory in New Mexico reveals their intricate patterns and the filamentary nature of sunspot penumbras. Only a small portion of the solar surface is shown in this fine photograph. The center (umbra) of the large sunspot at bottom is half again as large as our Earth.



THE SUNSPOT CYCLE, 1610-1976. Sunspots come and go on the Sun in an irregular cycle of about 11 years, with some obvious long-term changes. Annual mean sunspot numbers (an average measure of spottedness of the Sun) are shown here for each year since the discovery of the telescope. Data on the earlier parts of the graph are less reliable than in later periods.

at the time of sunspot minimum very few are seen, and for periods as long as a month none can be found.

The last maximum of the sunspot cycle was in 1968-69, and the one before that, which was particularly strong, was in 1957-58. The next should come in early 1980. The last minimum of sunspots was in 1976. Skylab took its observations of the Sun in the declining phase of the sunspot cycle, as the number of spots decreased toward the 1976 minimum.

To the astronomer, this long, clear record of sunspot numbers is evidence that the magnetic disturbances responsible for spots are driven by some cyclic mechanism, probably involving the forces of the differential rotation of the Sun, at and below the level of the photosphere. The search for a complete description of the cause of sunspots and the solar cycle has been one of the long and continuing efforts of theoretical astrophysics.

Other interest in the sunspot cycle springs from its frequent association, in fact and fiction, with cyclic changes on Earth.

Soon after the sunspot cycle was discovered, more than a century ago, a strong relationship was noted between the number of spots on the Sun and the number of auroras that were seen in the northern (and later the southern) skies. A similar relationship was soon established between the number of sunspots and the state of Earth's magnetic field: When the Sun showed more spots, Earth's magnetic field was more frequently disturbed by violent "magnetic storms." In addition, it has been known for many years that the state of Earth's ionosphere—the ionized layer of the high atmosphere that makes possible long-distance radio communication—is affected very critically by solar activity, in step with the number of sunspots. In each of these cases, however, it is not the spots themselves that bring about the terrestrial changes, but other, less frequent and more dynamic events such as solar flares and eruptions in the chromosphere and corona. These events occur more often when the Sun is more spotted and active. Because sunspots are the most easily observed of all solar features, they have traditionally served as the storm warnings of the solar system.

Can these warnings also serve to predict more immediate effects on Earth, such as changes in our weather and climate?

This important question, so frequently asked, is not easily answered. Change in solar output is only one of a number of possible causes of change in the lower atmosphere of Earth. The Sun is a likely cause of long-term climate change—as measured in time scales of millenia, centuries, and possibly decades. It is also a possible cause of shorter term climate change. It is probably not a dominant cause of day-to-day or local weather patterns. These are at present only theories, because measurements and physical understanding in this area of solar and atmospheric physics are very limited.

Before more satisfactory answers can be given, we need facts in two specific areas of research. The first is the still unanswered question of what and how much change occurs in the various outputs of the Sun as the sunspot number waxes and wanes. This includes not only its various components of heat and light but also the flow of solar particles in the space between the Sun and Earth. The second need is for a more complete understanding of worldwide circulation, weather, radiation, and climate. Atmospheric physicists are now able to model the complexities of global weather and climate with advanced computers. On the solar side, future measurements from space should add much to the scattered data on solar output that now exist, especially from instruments or programs that continue through a complete solar cycle of 11 years or more.

Granulation

The photosphere, in spite of its white-hot temperature and intense magnetic fields, is a relatively quiet layer of the Sun, as compared with the more turbulent layers above it. But closer looks at the white light surface, with good telescopes under good observing conditions, reveal an overall pattern of change and motion. The photosphere, under high magnification, appears completely covered with an irregular pattern of cells called granules, which look something like the polygonal cells of a honeycomb.

To scientists who study fluid and gaseous motions, these cells betray the presence of convection, as in the case of turbulent, billowing clouds or bubbles in a boiling pot. Convection in the photosphere carries hot gas upward in globs or cells; these granules radiate some of their heat

energy and then sink back down. Individual cells move up and down at relatively slow speeds (about 18 km/min and last about 8 min, on the average, before breaking up; the solar granulation pattern is thus constantly changing. Although individual granules are hard to detect at our distance from the Sun, they are about 1800 km in diameter, nearly half the size of the continental United States. As we shall see, the up and down motions of the photospheric granulation become more evident and amplified in the solar layers above the photosphere.

Skylab observed the photosphere in white light with several instruments and kept its own photographic record of sunspots, chiefly for comparison with observations in other wavelengths and with solar observations made on the ground during the Skylab mission.

THE SPECTRUM: Sunlight, which is the visible portion of the total solar electromagnetic spectrum, bends as it passes through a glass prism. The different wavelengths that make up this light are bent by a different amount, thus separating them and revealing their characteristic colors. Red, the longest wavelength, is bent the least. Separation through a prism is called refraction. Separation can also be achieved with diffraction gratings. In the diffraction technique, the light is reflected by a grated reflective surface rather than refracted through a transparent medium.

Through the Spectroscope: the Chromosphere, Corona, and Prominences

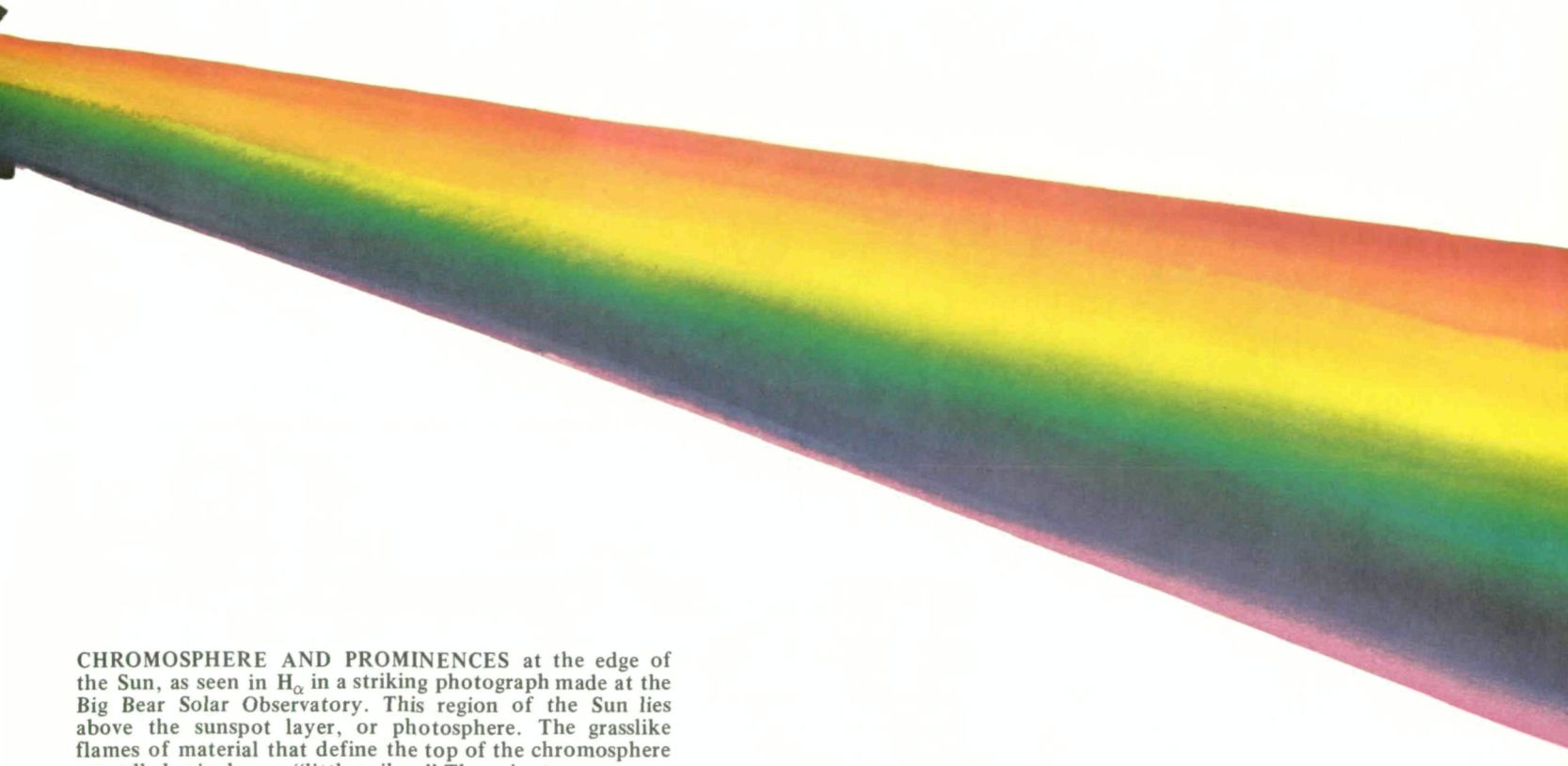
Above the photosphere and sunspots lie two extensive regions of the Sun that we can call its outer atmosphere—the chromosphere and corona. The chromosphere, or "color sphere," is a layer several times thicker than the photosphere. It is still a thin layer, extending above the photosphere to a minimum height of about 2000 km. It ends in a ragged, irregular boundary with occasional spiked extensions, called spicules, that shoot up an additional 5000 to 15 000 km into the vaporous "crown of the Sun" or corona. Spicules rise and fall like choppy waves on a stormy sea, in periods of 5 to 10 min. The top of the chromosphere, like the top of the ocean, is thus in constant and dynamic change.

The density in these high layers of the Sun is but a fraction of that in the photosphere, which is itself nearly a vacuum like that of the uppermost atmosphere of Earth. Because they are so diffuse and so much fainter than the photosphere, the chromosphere and corona cannot be seen with the naked eye or simple telescope. They can be detected, momentarily, at eclipse, when the Sun blots out the photosphere, or seen in more limited fashion by carefully excluding the glare of the solar disk and looking at the extreme limb of the Sun with instruments designed for the purpose. A most useful tool for observing these outer regions—and their real discoverer—is the spectroscope, which can be used to sort out and isolate solar rays that come from specific regions of the Sun.

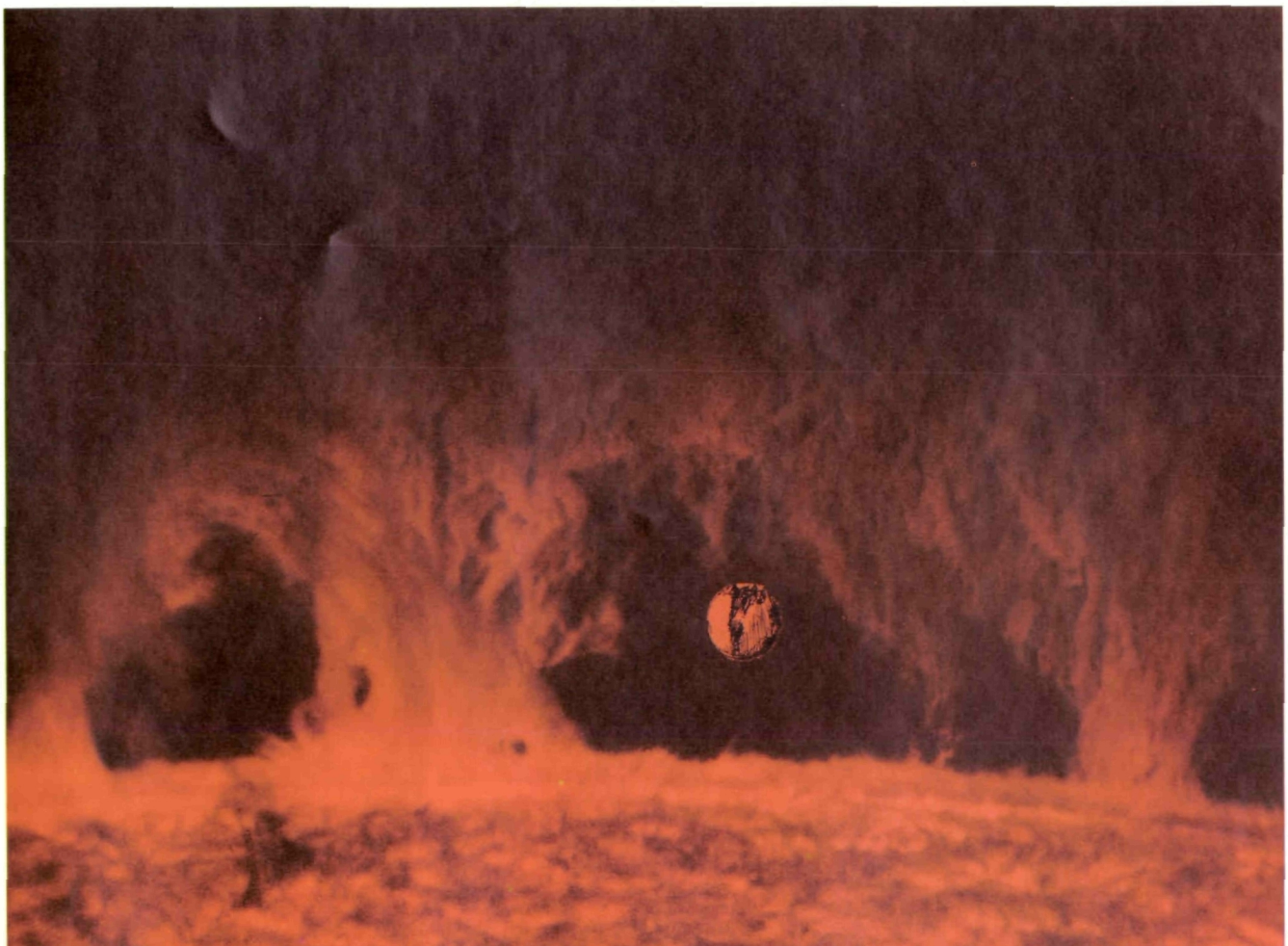
Physical Conditions in the Sun's Outer Atmosphere

One of the early surprises of solar physics, and for many years one of its perplexing problems, was the elevated temperature of the Sun's outer atmosphere. We generally expect temperature to decrease with distance from a radiating surface. The temperature drops, for instance, as one moves away from a radiator, or the surface of a stove. We would therefore expect the temperature of the solar atmosphere to drop steadily with distance above the radiating photosphere. Instead we find that temperatures in the chromosphere and corona rise sharply and dramatically.

The explanation of this apparent anomaly rests on two facts: the photosphere is *not* a simple radiator of energy, and the conditions in the upper solar atmosphere are not controlled by radiation alone. Energy of another kind is present, and important, in the chromosphere and the corona—the energy of *motion* in granules, waves, and spicules. Astronomers now believe that some of the photosphere's energy is transmitted by these means to the thin upper atmosphere of the Sun, and there deposited in the form of heat. Meantime, actual radiation from the photosphere seems to pass unhindered and unabsorbed through the turbulent



CHROMOSPHERE AND PROMINENCES at the edge of the Sun, as seen in H_α in a striking photograph made at the Big Bear Solar Observatory. This region of the Sun lies above the sunspot layer, or photosphere. The grasslike flames of material that define the top of the chromosphere are called spicules, or "little spikes." They rise to an average height of about 5000 km above the photosphere and are dwarfed by the spectacular cloudlike prominences. Earth, about 13 000 km in diameter, is shown for scale.



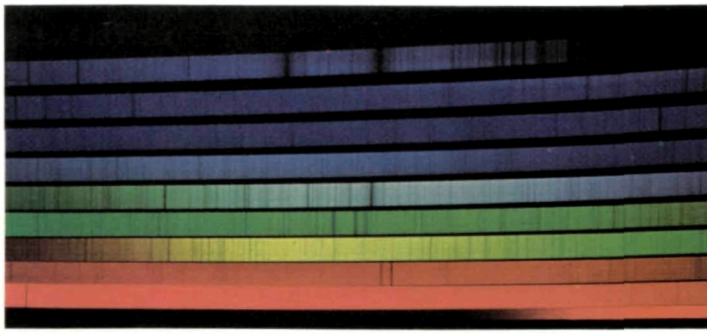
chromosphere and corona. The two mechanisms produce two different effects: (1) radiation pours out the energy that we see and feel on Earth and (2) convection and mechanical motion create and maintain the hot, active, and nearly invisible outer atmosphere of the Sun itself.

Most of the kinetic energy of the granules is deposited in the chromosphere. There, after a slight initial fall, the solar temperature takes its upward turn. While the density drops rapidly (from about 10^{16} to about 10^{9} particles/cm^3) the temperature rises from a minimum of about 4300 to about 500 000 K.

At total eclipse, the chromosphere appears to the naked eye as a momentary bright pink band at the very rim of the Sun. It has been seen in this way in fleeting form since at least the early 18th century; but it took the spectroscope to identify the chromosphere as part of the Sun, and to reveal its peculiar physical properties.

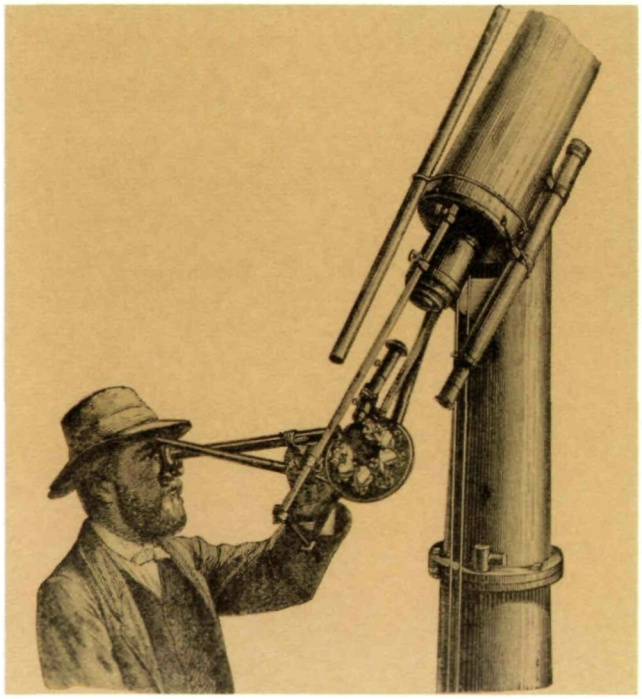
The Spectroscope

The spectroscope, in simplest form, is a glass prism that separates ordinary white light into its component wavelengths or colors; red, orange, yellow, green, blue, and violet. An added eyepiece or projection lens allows the user to see the spectrum clearly and sharply. When a camera replaces the eyepiece, the instrument is called a "spectrograph," which records images of the spectrum called "spectrograms." Other instruments, called "spectrometers," measure the spectrum quantitatively to produce numerical values for the intensity at each wavelength.



SPECTRUM OF VISIBLE LIGHT from the Sun shows a continuum of colors crossed by dark absorption lines; the light was white when it entered the narrow slit of a spectrograph. Wavelength decreases from bottom to top and left to right. Darkest red at bottom left is the border of the infrared; at top right the ultraviolet begins. Hundreds of dark absorption lines cross the stacked rainbow of colors: each line is the distinctive mark of a particular ion of an individual chemical element. The first dark red line at bottom left is α of hydrogen. The dark pair of broader lines in violet in the top row at center are Frauhofer's H and K lines of singly ionized calcium.

A 19TH CENTURY SPECTROSCOPE attached to a telescope for solar work; at the eyepiece is J. Norman Lockyer, a leading solar astronomer of Victorian England.



Sir Isaac Newton first explained how white light is separated into a rainbow of colors by a prism. Not long after, in 1802, another English physicist, William Wollaston, tried more elaborate experiments with the spectroscope and sunlight. To determine whether sunlight was made up of finer divisions than the broad blur of colors, he inserted a narrow slit between the incoming sunlight and the prism so that images of the slit would show up in the colored spectrum. Wollaston, who was partially blind, found that the normal rainbow of color of the solar spectrum was then crossed by seven dark lines—two in the red region, three in the yellow-green, one in the blue, and one in the violet.

In the following decade Joseph von Fraunhofer, in Munich, performed the same experiment more carefully. He found more than 500 of these dark divisions, which have come to be known as Fraunhofer lines.

Later improvements in instruments revealed more and more lines in varying strengths and

CHARLES A. YOUNG, with a prism spectroscope, at the solar eclipse of May 28, 1900, at Wadesboro, N.C.

widths. Prisms, by and large, have been replaced by ruled gratings in modern spectographs to achieve high spectral resolution. Today we know that lines in the solar spectrum exist in almost countless number, and that Wollaston and Fraunhofer detected only the darkest and most distinct.

Later 19th century physicists established the remarkable significance of the Fraunhofer lines: each is the unique signature of a distinct chemical element at a distinct stage of ionization in the solar atmosphere. The line seen by Wollaston in the violet part of the spectrum is due to the presence of singly-ionized calcium, for instance; and the strongest of the lines he saw in the yellow is due to neutral, or nonionized, sodium. The line in the blue and one of those in the red are marks of solar hydrogen.

It was later shown, by laboratory experiment,

that the darkness or intensity of each Fraunhofer line is an indication of the amount of the element present, and its width a measure of the temperature and pressure at its source. Slight shifts in the positions of the Fraunhofer lines reveal the presence of motions on the Sun, for velocity of the source changes the wavelength of radiation, by the common phenomenon of doppler shift. It was from these spectrum shifts that sunspot and granulation motions were detected and studied. Other characteristics of the lines can be interpreted to reveal other physical quantities. Magnetic fields, for instance, cause certain spectral lines to blur and split. The work of deciphering the message of the solar spectrum continues today, as laboratory and theoretical studies uncover new methods of interpreting information hidden in the spectrum of the Sun.

Spectra of Photosphere and Chromosphere

Since each layer of the solar atmosphere is characterized by a distinct range of temperature and pressure, each displays its own distinctive spectrum. The spectrum of the photosphere, as we have seen, contains thousands of fine, dark Fraunhofer lines on a bright background, or continuum, of color. The spectrum of the chromosphere, on the other hand, is a reversal of the photospheric spectrum—the continuum of colors is much weaker, and at the wavelengths where dark Fraunhofer lines appeared in photospheric spectra there now appear lines that are brighter than the background. These bright lines are known as emission lines. The brightest of the chromospheric lines in the visible light spectrum corresponds with one of the dark lines seen by Wollaston in the red part of the spectrum, due to hydrogen. Under chromospheric conditions of low density and high temperature, hydrogen emits red light in this narrow spectral region, which is known to astronomers as the H_α line. It is this red emission line that gives the chromosphere its rosy tint and its name.

Spectrum of the Corona

Above the chromosphere, in the solar corona, the spectrum is altogether different; a very weak continuum of color is crossed by only a few lines. These are faint emission lines, only slightly brighter than the background continuum, with positions (i.e., wavelengths) that do not match any of the Fraunhofer lines.

The anomalous spectrum of the corona was first observed on August 7, 1869, at a solar eclipse in Iowa. With a prism spectroscope in a makeshift observatory in Burlington, the American astronomer Charles Young found a strange green emission line in the outermost atmosphere of the Sun. William Harkness, watching the same eclipse with a U.S. Naval Observatory party in Des Moines, observed the same feature. The coronal green line, and others like it, which were discovered at subsequent eclipses, defied explanation for many years.

Spectral lines of the photosphere and chromosphere were associated, one by one, with chemical elements found on Earth, but the lines from the coronal spectrum matched nothing that could be reproduced in the laboratory. For about 70 years they were ascribed to a hypothetical new element, coronium. In 1940 the emission lines of the corona were finally recognized as features of common metals at extremely high temperature and very low densities. This discovery gave the first clear indications of the true temperatures of the Sun's corona—10^6 K and more. The green coronal line was shown to be due to atoms of iron, which at these million-degree temperatures and vacuum densities lose half their electrons in successive ionization stages. Other coronal lines in the visible spectrum correspond, we now know, to iron, calcium, nickel, and other heavy elements, which are even more highly ionized, revealing the existence of local regions in the corona that are even hotter.

Spectrum of the Chromosphere

Charles Young was also the first to see the reversed spectrum of the chromosphere. In 1870, the year following his Iowa discovery, Young took the same spectrograph to Spain to observe the next total solar eclipse, which would occur 3 days before Christmas. For this eclipse he kept the slit of the spectrograph tangent to the extreme edge of the Sun so that, at the instant of totality, he might see the unknown spectrum of the chromosphere. During the partial phase, as the Moon covered the last bit of the Sun, he watched the colored continuum and dark lines of the photospheric spectrum fade. Then, at the instant when the

photosphere was completely covered, Young saw the Fraunhofer lines flash from dark to bright, revealing the hidden secret of the chromosphere. It lasted but 2 seconds.

Young's description of this important discovery is a classic in the literature of the Sun:

> . . . the dark lines of the spectrum and the spectrum itself gradually faded away; until all at once, as suddenly as a bursting rocket shoots out its stars, the whole field of view was filled with bright lines more numerous than one could count.
>
> The phenomenon was so sudden, so unexpected, and so wonderfully beautiful, as to force an involuntary exclamation.

On his return to America, Young continued his studies of the spectrum of the chromosphere, first in the observatory of Dartmouth College and later in the clear high-altitude air of the Continental Divide.

At the summit of the newly laid Union Pacific Railway, near present-day Tie Siding, Wyo., Young spent the summer of 1872 close to the eyepiece of his telescope, waiting for the sporadic moments when he could best observe the extreme edge of the Sun. During this time he identified and studied over 200 emission lines in the chromosphere. He noted, among other things, that the strength of the chromospheric lines varies from day to day and from position to position around the Sun—an indication that the chromosphere is an active and constantly changing region.

Another dedicated observer who spent many years at the eyepiece of a spectroscope studying the edge of the Sun was Father Angelo Secchi of Rome. Secchi was particularly interested in the ragged upper boundary of the chromosphere, which he described in 1877 as "a burning prairie." In common with other astronomers of his day and since, Secchi was also interested in the larger, more spectacular features at the solar limb called prominences.

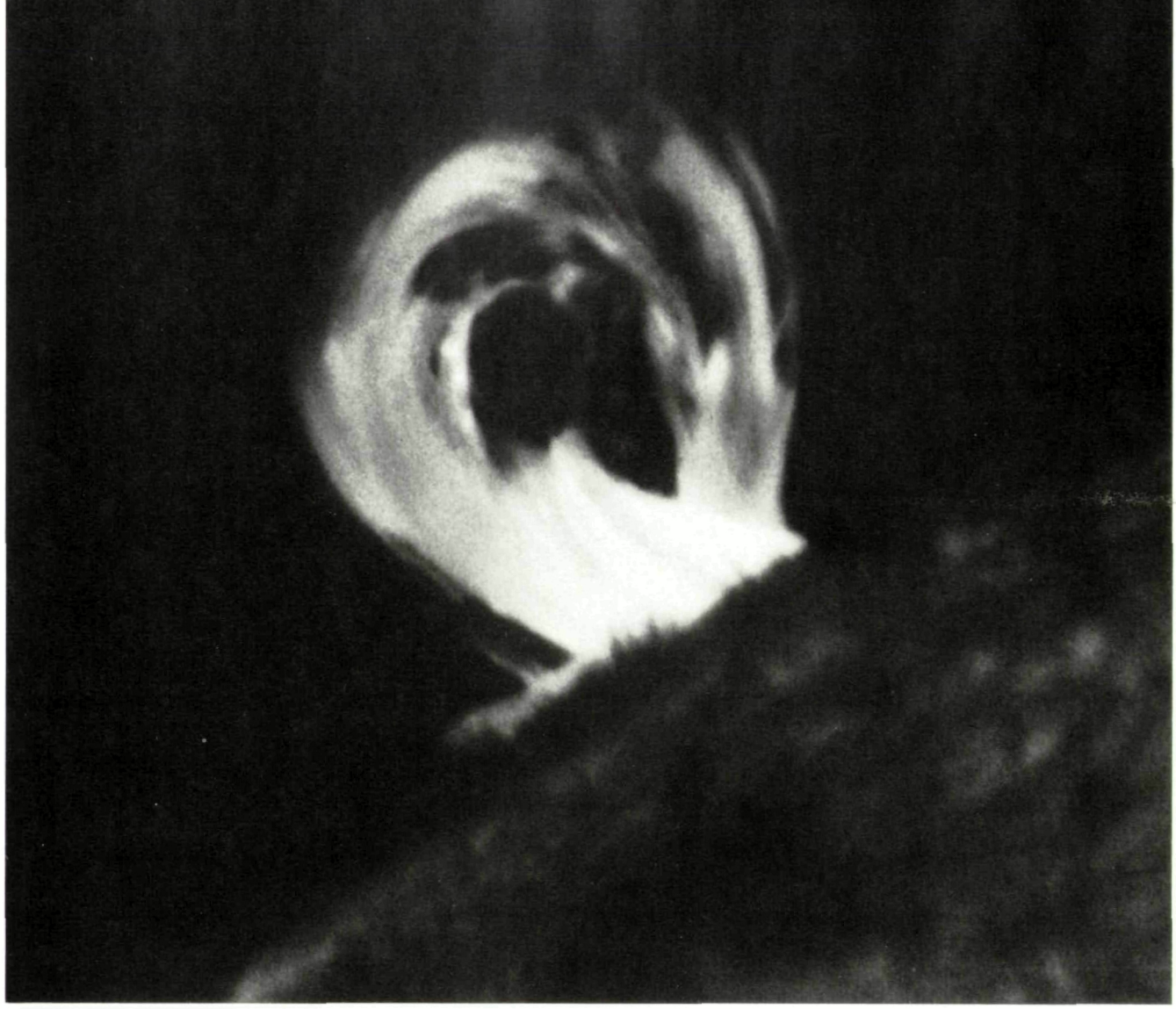
Solar Prominences

Like the chromosphere, prominences were first seen at eclipse.

During a total solar eclipse, when the Sun is covered, occasional solar prominences appear above the edge of the Moon like red clouds standing well above the top of the chromosphere. They can be seen outside the eclipse with spectroscopes and other special instruments. The smallest prominences are about the size of Earth, and some have been seen that are as large as the Sun itself. Their temperatures, densities, and, therefore, their spectra are like that of the chromosphere, and we now consider prominences as cooler, denser chromospheric material that extends into the hotter, rarer, corona.

Prominences appear in many forms. Some develop into explosive features that lift off the Sun as great eruptions into space. Some take the form of large and delicate loops, in which material appears to rain downward, as though condensing from the corona to fall on the chromosphere below. Others are quiet and lasting features of the solar atmosphere that persist for weeks and months without major change. Their elaborate and varied forms, drawn and cataloged by generations of solar astronomers, are now explained as the result of

COMPLEX SOLAR PROMINENCE seen at the limb of the Sun in H_α at the Sacramento Peak Observatory on December 7, 1970. These flamelike extensions rise nearly 240 000 km above the solar surface, following the form of magnetic field lines.



FLAMING LOOP PROMINENCE seen nearly edge-on at the solar limb in H_α at the Big Bear Solar Observatory on August 3, 1970. The physical conditions in prominences are much like those of the chromosphere in which they appear to be rooted.

arched lines of magnetic force that connect strong regions of opposite magnetic polarity in the photosphere and chromosphere. Heavy material in quiet, or quiescent, prominences is supported in the lighter corona by a kind of buoyancy of the magnetic lines of force. Loop-shaped prominences and many of the more active and eruptive forms reveal the presence of cooler material in the corona that is trapped in arched magnetic lines, much as electrons and protons are trapped in the van Allen belts of Earth's magnetic field.

The spectroscope, which has provided us with almost all we know about the Sun, remains the astronomer's most powerful tool. In various forms and modifications, such as the spectrograph, spectroheliograph, and the magnetograph, it is the basic instrument of all modern solar research, and an essential part of every solar observatory. Skylab carried five solar spectrographs, each expressly designed to observe important regions of the solar spectrum normally blocked by Earth's atmosphere.

THE SUN IN SINGLE WAVELENGTHS

Light from the disk of the Sun comes from a variety of levels in the solar atmosphere. Different colors, or more precisely, different wavelengths, come from different regions of temperature and pressure that correspond to different heights. Light at the red end of the visible spectrum originates on

THE SEETHING SUN SETS behind a western mountain range, revealing a red and angry face that few have ever seen. This telephoto photograph was made through a National Oceanic and Atmospheric Administration solar telescope in Boulder, Colo., through a narrow color filter that transmits only light in the red H_α band, portraying the active chromosphere with bright plages and dark prominences and sunspots. In this restricted light, mountains and climber appear black.

the Sun at a slightly lower level in the photosphere than does light at the violet end, and when we look at the disk of the Sun in simple white light—which is a composite of all visible colors—we see a composite, or average height. By looking at the Sun in specific colors we can see specific layers. This can be a powerful tool in probing the solar atmosphere.

The advantage is greatly increased when we choose not broad bands of color, but the specific, narrow wavelength regions of the Fraunhofer lines—when we choose, for example, not red or orange or yellow but one of the strong lines within one of those regions.

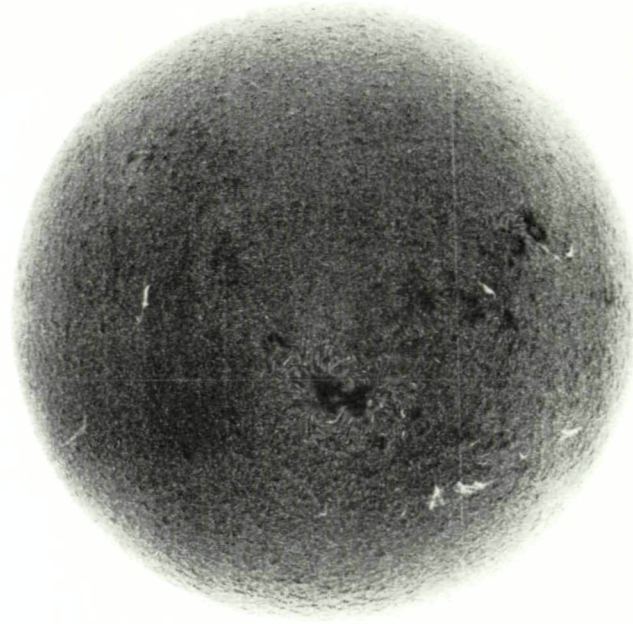
Solar radiation in the wavelengths of the dark absorption lines comes from regions of the solar atmosphere that lie above the average level of the photosphere—from the higher parts of the photosphere and the chromosphere above it. Different lines and different parts of individual lines originate in different, distinct layers. As a rule, the weaker lines come from lower regions of the solar atmosphere; the stronger lines sample higher regions. The darkest central cores of the strongest lines in the visible spectrum come from the high chromosphere—the level of the spicules seen at the Sun's limb by Secchi.

In scanning through the visible spectrum with a spectroscope we can scan in depth through the photosphere and the chromosphere, much as with a terrestrial spyglass we can examine closer and more distant scenes by adjusting the focus. The deepest we can see into the Sun with our spectroscopic probe is the low photosphere, in the continuum between the lines at the red end of the spectrum; the highest in the upper chromosphere, sampled in the centers of the strongest lines. We can see much higher than the chromosphere by tuning to the continuum and lines of the very short wavelength ultraviolet and X-ray spectrum.

The astrophysicist uses this spectroscopic "tuning" to probe the physical conditions of the Sun and its specific features. If he directs the slit of his spectroscope on a sunspot, for example, he can examine the different levels of the spot and the atmosphere above it by examining different lines and continuum regions in the sunspot spectrum. From these parts of the spectrum he can reconstruct the various levels that make up the sunspot and determine the temperature, density, motions, and even magnetic field at each level. At any level, however, he will see in the spectrum only that portion of the sunspot that lies within the area of the spectroscope slit, in general a thin strip on the Sun about 1000 km wide. He can move the slit of the spectroscope across the sunspot to compare different parts of it, but he cannot see the entire spot simultaneously. It is much like looking at a picture on a television screen that has only one horizontal scan line; alternations of bright and dark are apparent, but we see only a slice of the full scene and must imagine the rest of it.

The Spectroheliograph

The benefit of seeing an entire image of the Sun in a narrow spectral region was obvious to the earliest users of the spectroscope. This hope was realized in 1889 by an undergraduate at MIT who

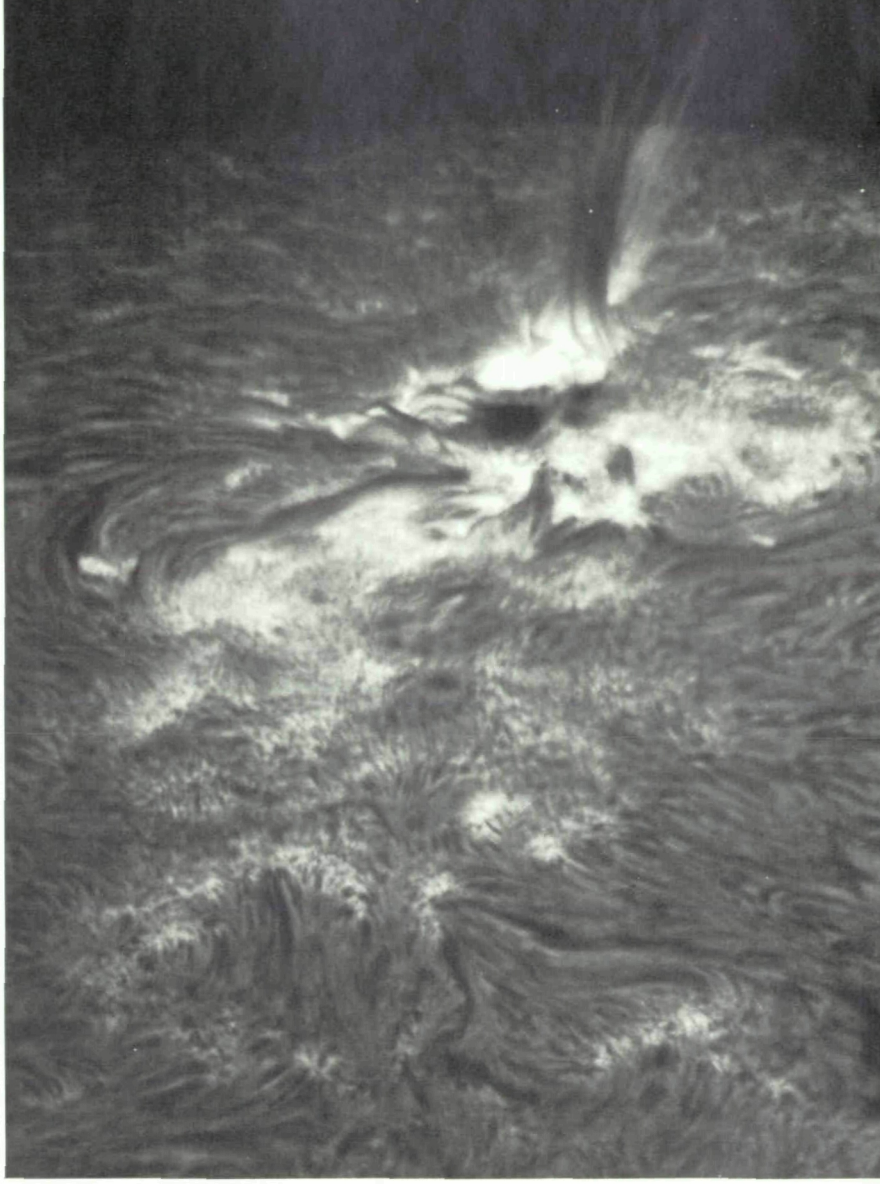


SPECTROHELIOGRAM made in H_α at the Mt. Wilson Observatory in California. Pictures of the Sun made in this way show us the solar chromosphere that lies between the sunspot layer (photosphere) and the corona. This exceptional example is printed as a "negative" so that prominences (filaments) on the disk appear lighter than the background. The large dark area at lower center is an active region, or chromospheric plage, that overlies an unseen sunspot group. The patterns of spicules are clearly seen over the disk, arranged in a pattern known as the chromospheric network.

modified a spectrograph at Harvard so that it would produce photographic images of the full Sun in a single spectral line. He did it by building up overlapping images of the spectrograph slit on a moving photographic plate. The young astronomer, then 21, was George Ellery Hale and the instrument was called the spectroheliograph. It produced single-wavelength, or monochromatic, images of the Sun called spectroheliograms.

Another avalanche followed, this time in our understanding of the chromosphere. For the first time man saw not just a slice but the entire seething, changing layer of the Sun that envelops the deceivingly quiet photosphere. A spectroheliogram of the Sun made in the center of the H_α or other strong Fraunhofer lines showed a face of the Sun that was surprising in its complexity and its violent change; it was covered with bright and dark areas that changed from day to day and from hour to hour and mottled with a networklike pattern of spicules.

In the 1930's, spectral filters were developed that were almost as effective as the spectroheliograph in isolating radiation of one wavelength, but that had the advantage of greater speed and better uniformity. These simple devices, which can be added to almost any telescope, have no moving parts. They screen out unwanted wavelengths by optical methods, transmitting only a narrow band, such as the H_α wavelength. When you hold such a filter in front of your eye and look at the Sun, you see the Sun in a single wavelength. In H_α, you see only the hydrogen in a certain temperature region on the Sun. Monochromatic filters are made in a variety of ways. The smallest is easily held in the hand and is very effective for viewing the chromosphere. One variety was used in Skylab's arsenal of solar telescopes for portraying the Sun in H_α.



FLARE SPRAY erupts in a plage in this close look at the chromosphere, taken in H_α at the Big Bear Solar Observatory on May 22, 1970. Hotter denser areas of the chromosphere appear brighter in H_α and define "plages" that lie above sunspot areas. The French name means "beach," for each looks like light-colored sand against the darker structures around them. The dark, seething spicules of the chromosphere stand out in this exceptionally clear picture of the Sun's most active layer.

Plages and Filaments

One of the more important discoveries in early spectroheliograms was the brightening of the chromosphere above sunspots. These brighter areas, which were given the French name "plages," (rhymes with "mirages") appeared before sunspots and lasted after the spots were gone; they were recognized as more fundamental indicators of solar activity than the spots themselves. The plages were evidence of hot, dense areas in the chromosphere that were likely seats of dynamic disruptions called flares. Plages were later shown to delineate regions of the chromosphere where strong magnetic fields were concentrated.

Spectroheliograms also gave extensive new looks at the solar prominences that previously had been seen only with spectroscopes at the limb of the Sun by scientists such as Secchi in his years of patient observations in Rome. Spectroheliograms made in the light of H_α showed prominences on the disk of the Sun, where they appeared as dark

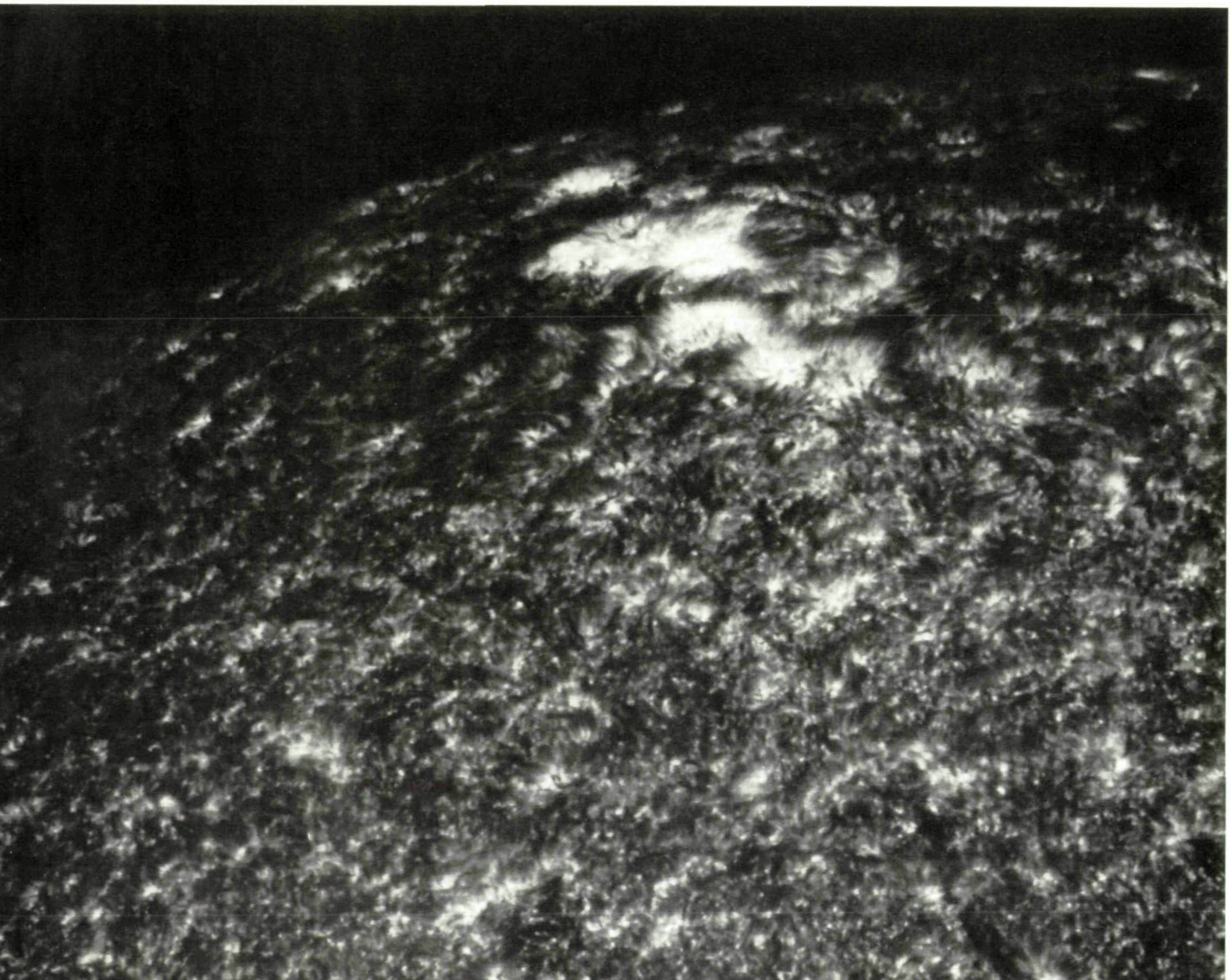
filaments against the bright chromospheric background. Continuous observations of prominences as they crossed the disk of the Sun revealed their real shape and size, lifetime, and relationship to sunspots and other features of the Sun.

Supergranules and the Chromospheric Network

In similar fashion, spectroheliographs showed spicules not just at the edge of the Sun, projected on the sky, but over the entire solar disk. They revealed that these spikes of chromospheric material were distributed over the Sun in a pattern that resembled a fishnet, and which came to be known as the chromospheric network. The spicule network outlines the boundaries of large cells in the chromosphere, encircling each cell like a fence of stakes.

The fenced-in areas were later shown to be giant circulation patterns, much like photospheric gran-

MOTTLED FACE of the upper chromosphere is seen in this high-resolution spectroheliogram taken by Bruce Gillespie at the Kitt Peak National Observatory on September 17, 1975. The picture was made in an extremely narrow region of a strong line of ionized calcium. Near the top is an active region, or "plage." Dark spicules are arranged in a subtle "network" pattern that covers the entire Sun. Each element of the net is a "super granule." These gigantic circulation cells are about 30 000 km in diameter and are bounded at their edges by a fence of dark spicules.



ules but on a scale 40 times larger. Like the photospheric granules, the chromospheric cells, called supergranules, cover the entire surface of the Sun. They are typically 30 000 km across and more or less circular in shape, persisting about half a day before being disrupted and replaced. Material in supergranules flows up in the center, spreads out to the edge, where the spicules are, and sinks back down. Supergranules are thus giant convective cells that are related to the smaller scale pattern of convective granulation that lies thousands of kilometers below in the photosphere. The heat and kinetic energy of the photospheric granules is transmitted, probably by wave motions, to the chromosphere, where new circulation patterns of grander scale are set up. Magnetic fields in the chromosphere are concentrated in spicules at the supergranule boundaries, where they are apparently pushed by the outward flow of material.

EXPLOSIVE FLARE erupts in the chromosphere, igniting a plage in a temporary flash of light. Flares such as this, seen in H_α at the Big Bear Solar Observatory on August 7, 1972, last from a few minutes to half an hour. During this time they release a prodigious amount of energy. A dark sunspot can be seen beneath the plage; around it are writhing spicules and dark loop prominences. All are associated with complex magnetic fields on the surface of the Sun.

Solar Flares

Monochromatic observations of the solar disk revealed for the first time the truly explosive features of the chromosphere called solar flares. Flares are sudden brightenings of limited regions of the chromosphere. By almost every measure they are the Sun's most catastrophic and energetic events. They have special importance to man, for they are known to produce effects that race through millions of kilometers of interplanetary space to rattle the upper atmosphere and magnetic field of Earth, altering the ionosphere and producing auroras and magnetic storms.

Flares last from a few minutes to more than an hour. They are confined on the Sun to relatively small areas; the largest cover but a few tenths of a percent of the solar surface. Flares occur in the chromosphere and corona, above the sunspot layer, but are related to the strong magnetic fields in spots. We see flares almost exclusively in bright plages that are associated with large and complex sunspot groups. Flares have little effect on the sunspots themselves and are hardly noticeable on the bland, white light face of the Sun. Only one flare was observed in white light before the days of the spectroscope, and only a handful before the days of the spectroheliograph and monochromatic filters, which have provided much of what we know about flares.

When flares are seen near the limb of the Sun in a monochromatic picture, they are sometimes accompanied by the spraying out of visible material, although not all flares are associated with ejections of this sort. Some on the disk of the Sun appear more like the sudden ignition of a pool of gasoline.

For many years solar observatories of the world have kept up an almost continual patrol for flares, chiefly by making continuous photographs of the Sun in H_α, with automatic cameras equipped with monochromatic filters. If a flare occurs, and if the sky is clear, the camera will record it in successive frames. Related, but harder to achieve, are efforts to record the spectra of different kinds of flares from start to finish. This requires more constant vigilance and quick responses to direct the spectrograph slit at the specific area of the Sun where a flare is starting. It has many of the aspects of hunting quail or other fast, elusive game that flash up unexpectedly and then are gone.

The vast body of data on solar flares has shown that they occur in an almost continuous range of energy and size, from the largest to events so small that they normally escape detection in visible

wavelengths. Flares occur in step with the sunspot cycle: the more spots on the Sun, the greater the probability of a flare. The largest flares occur most often at the time of maximum sunspot number, although not exclusively then. At times of maximum sunspot number we expect to observe a small flare every hour or two. At the time of sunspot minimum, days and weeks transpire without an observable event.

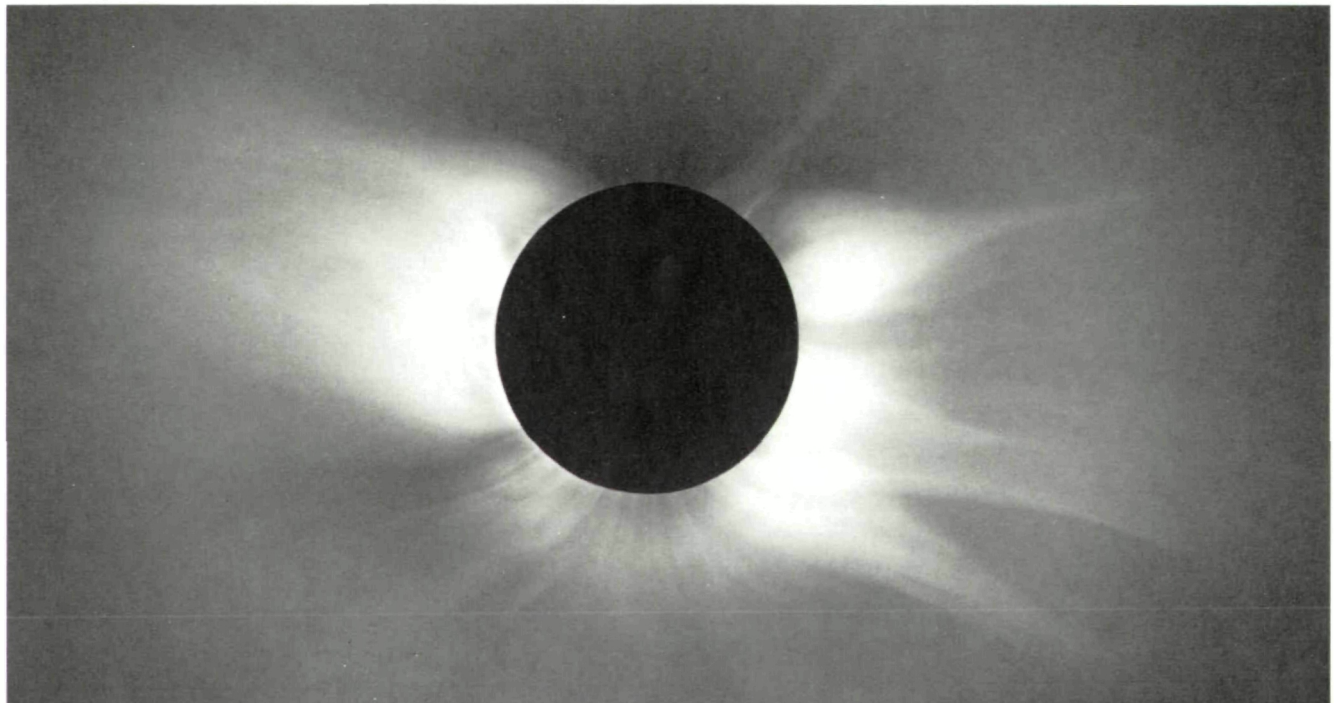
The continuous patrol for flares has shown that they are associated with distinctive features in the chromospheric magnetic field, in plage regions where the field is most concentrated and intense. Solar flares are now believed to result from the sudden conversion of magnetic energy to the energy of heat, light, and motion. We can appreciate the strength of the chromospheric magnetic fields when we realize that a large flare releases energy equivalent to the explosion of 10 million hydrogen bombs in a few minutes' time. The small fraction of this energy that our tiny Earth intercepts is adequate to produce striking effects in our upper atmosphere, even at our great distance from the Sun. These effects are produced by the ultraviolet, X-ray, and energetic particle emission from flares, and not by an appreciable change in the overall output of the Sun at the time. Flares, although spectacular, add only slight amounts to the total energy received from the Sun—at most about a thousandth of a percent, and that for only a few minutes.

Spectra taken from the ground soon revealed that in H_α and other parts of the visible region we see only a small part of the total radiation of flares. Because flares give evidence of very high temperatures, we expect other strong radiation in the ultraviolet and X-ray regions. Radiation from the Sun in these regions can be observed only from above our atmosphere, making the normally difficult tasks of hunting and recording flares even harder. Early solar rockets succeeded in recording ultraviolet and X-ray emission from the later stages of flares, and the first solar satellites provided early spectral information. But it was left to Skylab to record complete spectra of flares from start to finish with high-wavelength discrimination throughout these important spectral regions. This was the most difficult single challenge of the solar observing program on Skylab.

THE MAGNETIC SUN

Shapes and forms seen in the corona at eclipse, particularly at the rotational poles of the Sun,

THE SOLAR CORONA, seen from East Africa during the total eclipse of the Sun that occurred on June 30, 1973, reveals shapes suggestive of magnetic lines of force. Rays of light emanating from the poles of the Sun (bottom) look like the patterns taken by iron filings sprinkled over the poles of a bar magnet. Pictures like this suggested the presence of magnetic fields on the Sun long before they were actually measured. We now know that fields at the poles of the Sun are about as strong as the magnetic field of Earth; in sunspots and active regions they are thousands of times stronger.



resemble patterns taken by iron filings sprinkled over a bar magnet. These appearances led 19th century astronomers to question whether the Sun, like Earth, had some kind of basic magnetic field. Other evidences for possible magnetic forces on the Sun were noted in the arrangement of spicules and other features of the chromosphere above sunspots, as observed with the spectroheliograph.

It was only speculation until June of 1908, when George Hale, the inventor of the spectroheliograph, made the first measurement of magnetic fields on the Sun—in sunspots, as observed at Mt. Wilson solar observatory in southern California. The discovery revolutionized the study of the Sun. In finding strong magnetic fields in sunspots, Hale discovered the force for almost all solar activity and the basis for much of modern solar astrophysics.

The Zeeman Effect

Magnetic fields on an object as distant as the Sun cannot be measured directly. Hale's method in 1908, still used today, measures the field indirectly, through its effects on the spectrum. Hale looked closely at the spectrum of light from a sunspot and compared it with that from an unspotted region of the photosphere. One of the significant differences, which had been noted as early as 1892, was a splitting of certain lines of the sunspot spectrum. For example, the Fraunhofer absorption line from iron at a wavelength of 5941 Å, in the red part of the solar spectrum, appeared in sunspot spectra as a close pair of lines, very slightly separated. The same line, outside a sunspot, appeared single. Certain other lines were blurred, or widened, in sunspots.

Shortly after doubled lines were first seen in sunspots, the Dutch physicist Pieter Zeeman in laboratory study discovered that if a light source is placed in an intense magnetic field, certain of its spectral lines are broken into several components, producing split and blurred lines. Zeeman found that the amount of splitting is a measure of the strength of the magnetic field and the direction of the field relative to the observer's line of sight. The splitting is most pronounced when we look along the lines of magnetic force, rather than at right angles to them. Zeeman also noted that the separate components of a magnetically split line show different kinds of polarization, as detected by a polarizer, such as a modern Polaroid. In the simplest case, certain lines, when viewed along the direction of the magnetic field, were split into two components that showed opposite circular polarizations.

Sunspot Magnetic Fields

Many astronomers, following Zeeman's discovery, must have suspected that the blurring and splitting of spectral lines in sunspots were due to magnetic fields. But proof required careful demonstration, involving a good spectroscope of high resolving power, a good solar telescope at a favorable site, and, perhaps most of all, scientists who were involved in modern physics and its application to astronomy. At Mt. Wilson these conditions flourished, and in 1905 Hale set out to make the test. It took an effort of 3 years—an indication of the difficulty of the measurement—but at the end of that time he had the answer: Sunspots showed unmistakable evidence of strong magnetic fields, the strengths of which were several thousands times greater than the magnetic field of Earth.

Magnetic field strengths are commonly expressed in units named after the great German mathematician and physicist Karl Gauss. The strength of Earth's magnetic field, which orients our compasses, is about 0.3 G near the Equator. Near the terrestrial magnetic poles the field is about 0.7 G. In sunspots, Hale found fields of nearly 3000 G extending over sunspot areas many times larger than Earth itself. Fields of this strength and size are awesome sources of great energy. They completely dominate the distribution and motions of matter in their vicinity, and provide the forces that support prominences and explain flares. They also account for the lower temperatures of sunspots by inhibiting the normal flow of convective heat so that sunspots are cooler (and therefore darker) than the surrounding photosphere.

The discovery of magnetic fields in sunspots suggested a search in other areas of the Sun. Hale's method of detecting magnetic fields—by measuring the splitting of certain spectral lines—was limited by the resolving power of the Mt. Wilson solar spectrograph to very strong fields. Moreover, his method, and others used today, could detect only those magnetic fields or components of fields that

happened to be directed toward or away from Earth. Magnetic fields with lines of force perpendicular to the line of sight could not be measured. Another limitation was even more important. Hale was well aware that the field strengths he measured in sunspots, or elsewhere on the Sun, were averaged over a large area—the area of the Sun included in the long rectangle of the spectrograph slit—an a area at least 1000 km in short dimension. Hale pointed out that the averaging process probably concealed a host of fields of small size and possible large strength.

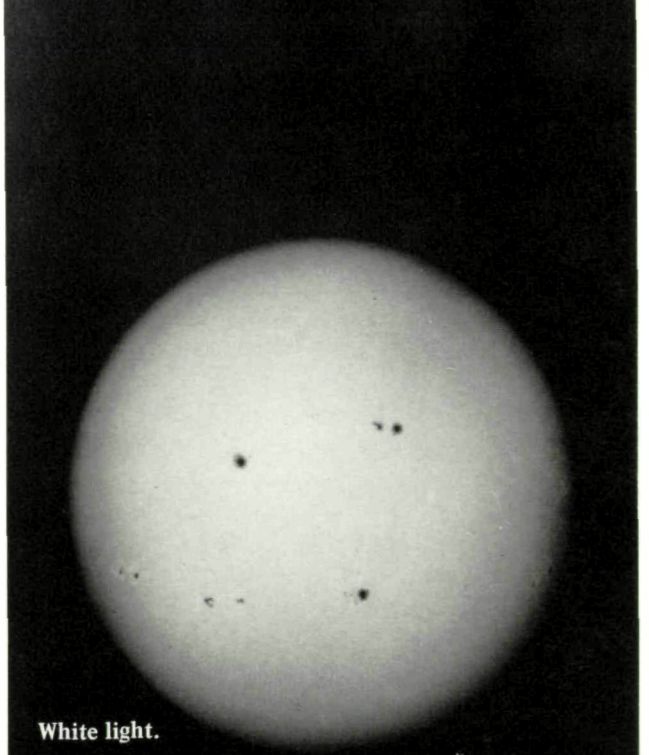
By 1918 Mt. Wilson astronomers thought they had found a weak, large-scale magnetic field at the rotational poles of the Sun. This was evidence, they felt, of a "general magnetic field" that had been proposed to explain the form of the polar corona. Its strength was at that time measured as 20 G—the lowest figure their instrument could measure.

Measurements With the Babcock Magnetograph

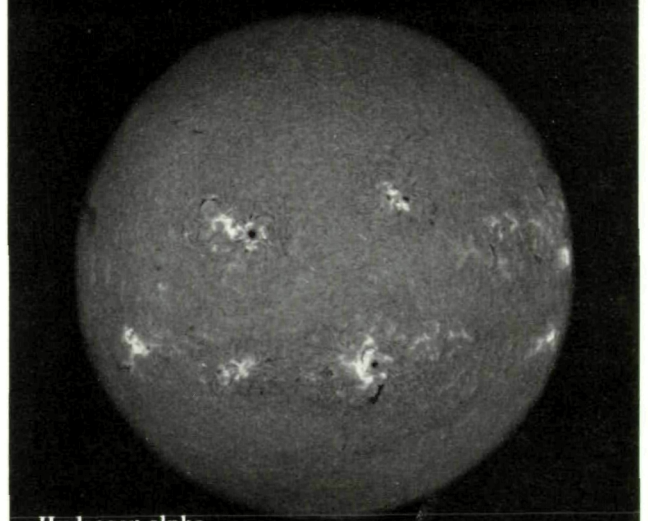
A dramatic improvement in techniques of solar magnetic field measurement was made at Mt. Wilson in 1952, when H. W. and H. D. Babcock developed a far more sensitive magnetograph. The Babcocks' instrument took advantage of the marked difference in polarization of the components of a magnetically split line. It employed better spectrographic equipment and newly developed photoelectric sensors to replace the older photographic plates. The result was a great improvement in sensitivity, so that fields of less than 1 G could be detected. This proved to be another important breakthrough in solar instrumentation and research.

The Babcock magnetograph revealed many classes of magnetic fields on the Sun that had escaped detection in earlier spectrographs. It found strong fields in the chromosphere wherever there were plages and concentrated fields in spicules at the supergranule boundaries. After later modification, it measured magnetic fields in prominences and in the low corona. The magnetograph found that flares most often occur along the neutral lines that separate regions of opposite magnetic polarity in the chromosphere.

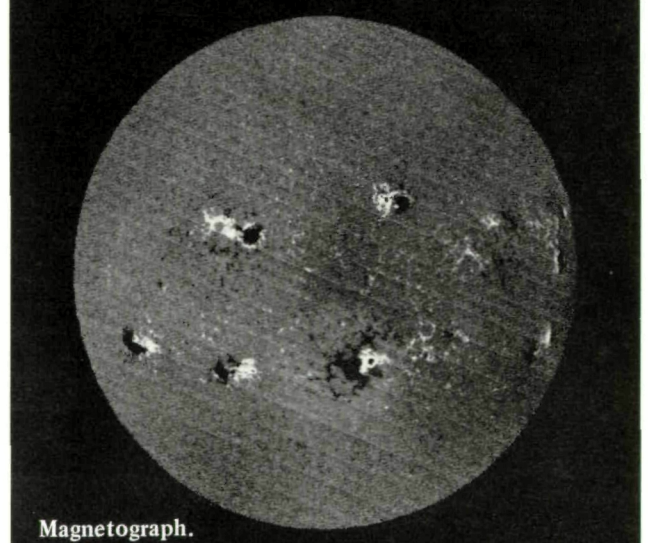
Study of accumulated magnetograph data over many years at Mt. Wilson showed that the surface of the Sun is divided into very large regions of common magnetic polarity and weak field strength



White light.



Hydrogen alpha.



Magnetograph.

that persist for many solar rotations. There are, at any time, as many as 20 of these large-scale, unipolar magnetic regions, with boundaries running more or less along lines of solar longitude, and of alternate magnetic polarity. One of the important discoveries from early space measurements demonstrated that this pattern of large-scale magnetic regions extended far above the Sun into interplanetary space, where it was detected by magnetometers on spacecraft at the orbit of Earth.

In the 1950's and 1960's the Mt. Wilson astronomers found evidence that the polar magnetic field of the Sun, the so-called "general field," reverses magnetic polarity each solar cycle, the change occurring at about the time of the sunspot maximum. A solar cycle later, the polarity switches back again, so that the complete magnetic cycle requires two sunspot cycles or 22 years. Hale had found much earlier that the polarities within sunspot groups seemed to reverse polarity in a similar way. In one cycle, the easternmost spot of a sunspot pair would have one polarity, and the western (following) spot of the same group would have the opposite polarity. In the next solar cycle the polarities would be reversed. The spot group reversals, and the apparent reversal of the polar field, imply that the basic cycle of solar activity is not 11 but 22 years.

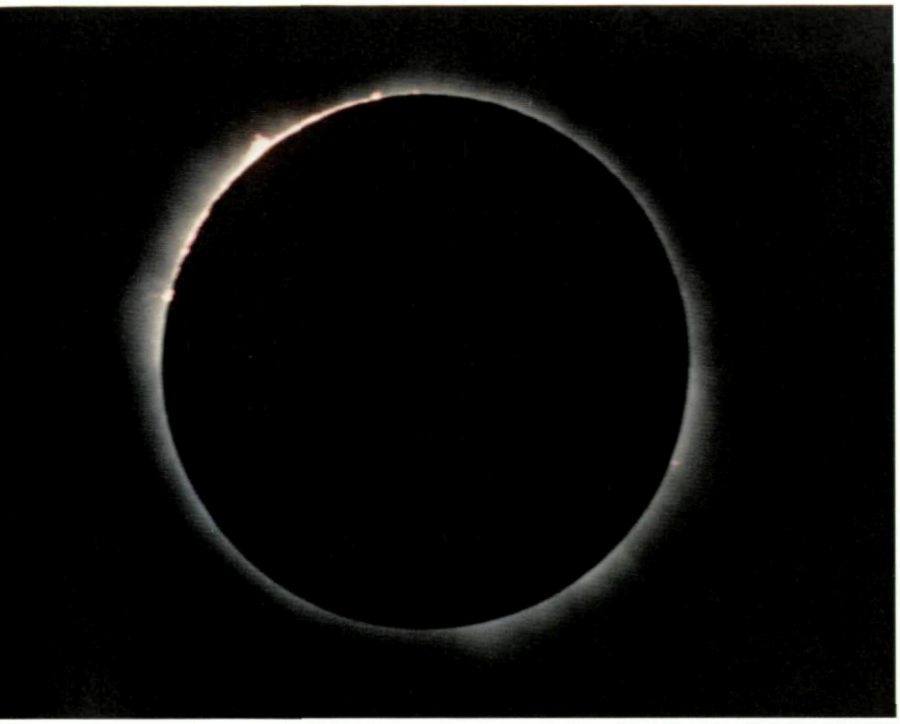
Modern measurements of the polar field of the Sun find it to be more nearly 1 G in strength, similar to that of Earth. It is thought to be the accumulation of surface fields that have drifted toward the poles of the Sun under the forces of differential rotation of the solar surface. This accumulated weak field near the poles of the Sun accounts for the form of the polar corona and for the misconception about a "general magnetic field" of the Sun.

Improvements in magnetographs have continued to the present day, with important advances in spatial resolution on the Sun. As expected, as we look at smaller and smaller areas on the Sun, we see evidences of finer and finer magnetic fields, with higher and higher field strengths, confirming Hale's suspicion that the averaging over large surface areas was hiding much of what the magnetic Sun had to show us.

THE SUN ECLIPSED

The parts of the outer atmosphere of the Sun—the corona and chromosphere—were first seen during total eclipses of the Sun, when the brighter photosphere is blocked momentarily by the Moon. Until about a century ago this was the only way the chromosphere could be studied, and until less than 50 years ago, the only way the corona could be seen. As a result, much of what we know today of these outer layers has come from the brief observations made at times of eclipse by many generations of astronomers over many years, often with great dedication, effort, and expense.

TOTAL ECLIPSE of the Sun by the Moon is shown in this composite photograph. The Moon's motion across the face of the Sun is seen in sequence from left to right, as more and more of the Sun is covered. As the last bit of solar glare is blocked by the Moon (center), the dim outer atmosphere of the Sun flashes out, as the white corona. This "total phase" lasts but a few minutes. Soon the Moon's motion uncovers a thin crescent of bright Sun and in about another hour the spectacle is over.



THE PINK CHROMOSPHERE flashes out from behind the Moon just as the last bit of the brighter Sun is covered at a total solar eclipse. A solar prominence rises above the chromosphere near the middle of the red arc. The dim blue light around the rest of the Moon is the lower corona. The chromosphere can be seen "edge-on" in this way for but a few seconds at eclipse, for the relentless motion of the Moon soon covers the thin layer. The chromosphere, or "color sphere," was named for its pink-red color, which is due to emission from the H_α line on the Sun.

Total Solar Eclipses

The path of the Moon about Earth is such that from time to time it passes exactly between Earth and Sun, casting the point of a moving, conical shadow in the direction of Earth. The pointed shadow does not always reach Earth, but when it does, it creates a small circle of night, at most about 300 km across, that races across the globe at supersonic speed.

An observer in the path of this small racing shadow will see the Sun's disk totally blocked by a black Moon for a few minutes. During this short time of totality he can see the red edge of the chromosphere (for a few seconds) and the faint, white corona (for a few minutes) against a dark sky. The sudden and ghostly appearance of the corona at a total eclipse is an impressive and moving sight that has never been completely captured in word or picture.

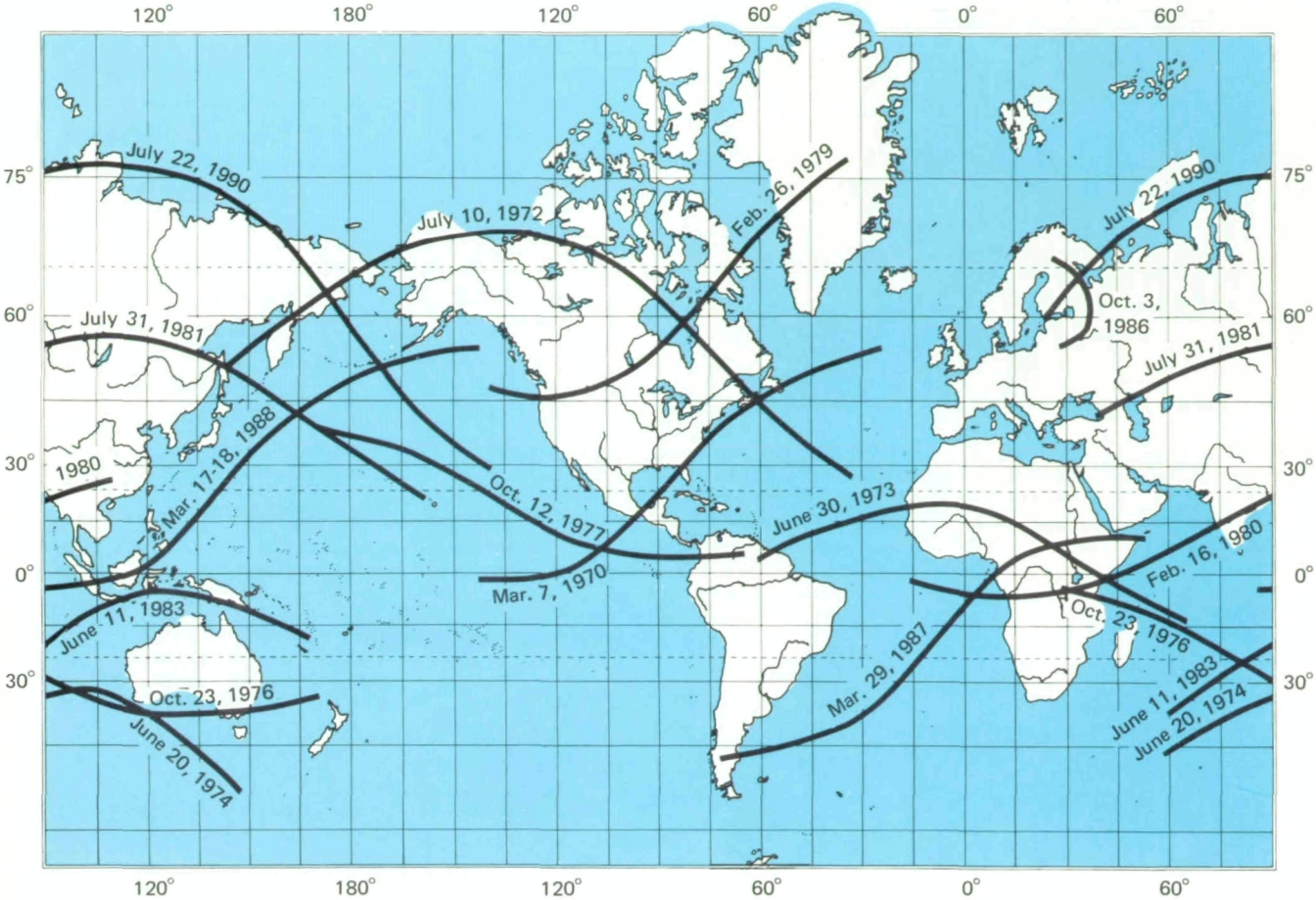
A total eclipse of the Sun occurs somewhere on Earth in two of every three years, on the average. It offers, for those in its narrow path, a time of totality that lasts at most 7 min. The average is about 2 min. In time, every place on Earth will be crossed by the moving shadow of a total eclipse, but, on the average, it is many hundreds of years between occurrences at the same place.

For many centuries, astronomers have been able to predict when and where solar eclipses will occur, and to hundreds of eclipses in all parts of Earth they have carried their telescopes to wait in the path of totality for a few minutes' chance to study the outer atmosphere of the Sun. The English astronomer Baily, for instance, traveled to Scotland to see his first eclipse in 1836 and to Italy in 1842 for his second. If an astronomer, then or now, made it his business to seek out and observe every total solar eclipse for 50 years, he could expect to accumulate a total of about 3 min's observation of the chromosphere and about 1 hr's observation of the corona, allowing for the chance that some of the eclipses would be blocked from view by clouds.

Until the early 18th century, astronomers used solar eclipses chiefly as tests of their ability to predict the orbits of the Moon and Earth, and to take data to refine their knowledge of the laws of celestial motions. A partial solar eclipse, and the partial phases of a total solar eclipse, were for these early astronomers almost as valuable as the rarer and more difficult to observe moments of totality. Few efforts were made to seek the precise places where a solar eclipse would be total, and fewer still attempted to observe the surroundings of the Sun eclipsed.

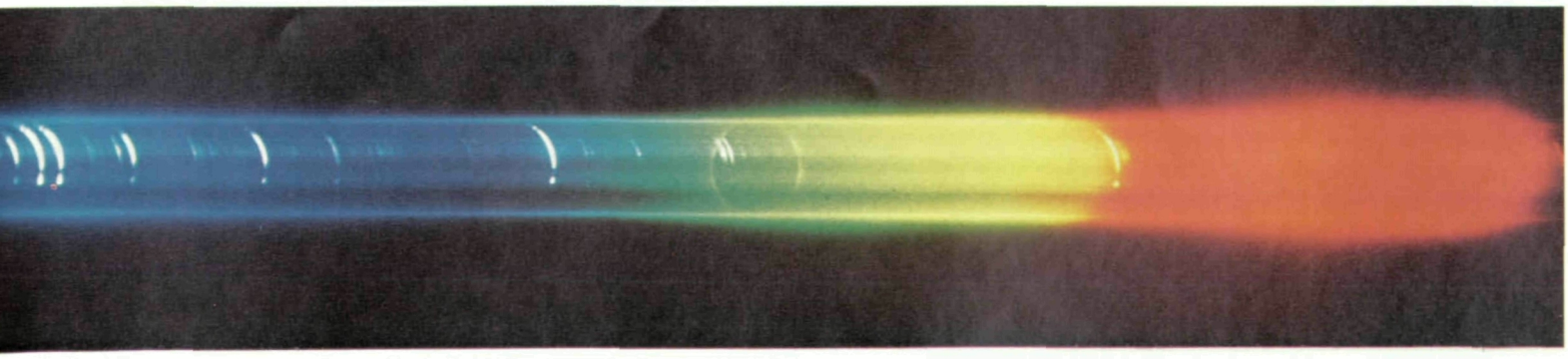
This may explain why we find no descriptions of the structure of the corona before 1715, and no descriptions of the red flash of the chromosphere and prominences before 1706. It took another century and more before eclipses were used to observe the Sun as a physical object, following the coming of photography and spectroscopy.

Interest in the chromosphere, prominences, and corona grew rapidly in the 19th century, and eclipse experiments were devised to answer the



CALCULATED TRACKS of total solar eclipses, 1970-90. In these 21 years, only 14 total solar eclipses occur and only two cross the United States. On the dates indicated, observers located along the paths shown will see the Sun fully eclipsed, but only for the few minutes when the shadow of the Moon races over Earth. During these fleeting minutes, the corona can be seen with ordinary telescopes.

SPECTRUM OF THE SUN AT ECLIPSE: The bright, arc-shaped lines are emission lines of the "flash spectrum" of the chromosphere. At times other than during eclipse, these same lines appear as absorption lines, darker than the colored continuum. When the photosphere of the Sun is blocked by the Moon, we see them "reversed," but only for a few seconds, just before totality and just after it. The full, thin circle of light in the green part of the spectrum is the green coronal line.



ASTRONOMERS from Princeton and the Royal Astronomical Society pose near Denver for the total solar eclipse of July 29, 1878. They had traveled far by ship and rail to see the Sun eclipsed for about 3 min. Charles Young (seated, second from right) was the leader of the expedition. His discoveries at times of eclipse were highlights of 19th century solar physics.

crucial questions of the origin of these curious appendages of the Sun. What caused the red prominences? Were they more than clouds? Was the corona a part of the Sun, or was it simply light scattered in Earth's atmosphere, like the glare around street lamps in fog? Could it be a lunar atmosphere, illuminated by the Sun? To arrive at answers astronomers needed more observations—careful observations of the detailed form and spectrum of the outer atmosphere of the Sun. As we have seen, the spectroscope allowed study of the chromosphere and prominences in full Sun, but the corona remained an elusive object, seen only at times of total eclipse.

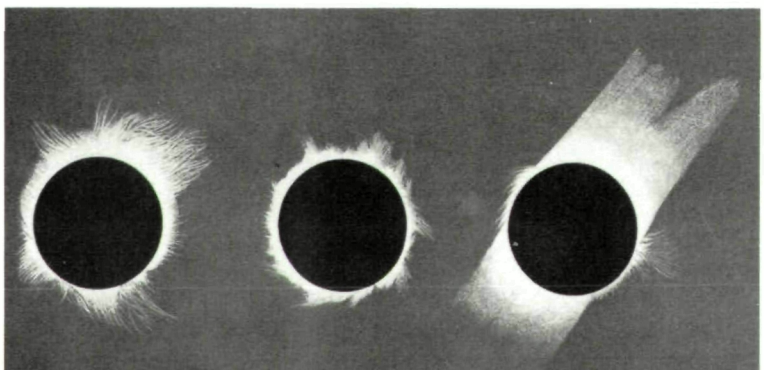
Drawings of the Corona

Photography was not available to assist in the quest until late in the 1800's; therefore, for many years and many eclipses it was standard practice to make drawings of the corona during the fleeting minutes of totality. This was done in pencil, chalk, watercolor, and oil. It was not an easy task, for the corona is made up of ethereal, wispy forms, and glows by eerie light; to many it appeared to shimmer and vibrate, apparently through optical illusion or emotional excitement; and the time alloted by nature to draw the corona was tantalizing at best, with no previews or second sittings. The sketchers, by and large, were not artists but astronomers, and a tense lot. They had traveled, typically, many thousands of kilometers and spent many months in preparation for a short, dramatic test of steady hand and unfailing eye. Some of the sketches were given to better artists, after the eclipse, for redrawing, which improved the quality and not always the accuracy of the portrait.

As a result, the collection of drawings, made with such difficulty, taught very little about the corona. They demonstrated that it was large and white and structured. But artists standing side by side often produced drawings that bore little resemblance to each other. By 1900, George Hale, then editor of the *Astrophysical Journal,* remarked in an editorial that

> . . . the experience of previous eclipses has shown that drawings of the corona for the most part serve no useful purpose unless it be to illustrate the personal peculiarities of the draftsman.

DRAWINGS of the solar corona during eclipse are not always reliable. Here three observers, standing side by side on a railroad siding in central Wyoming, recorded what they saw during the July 29, 1878, eclipse in three different ways. The center drawing was by the Territorial Governor of Wyoming, J. W. Hoyt, who traveled by train from Cheyenne to assist the visiting astronomers.



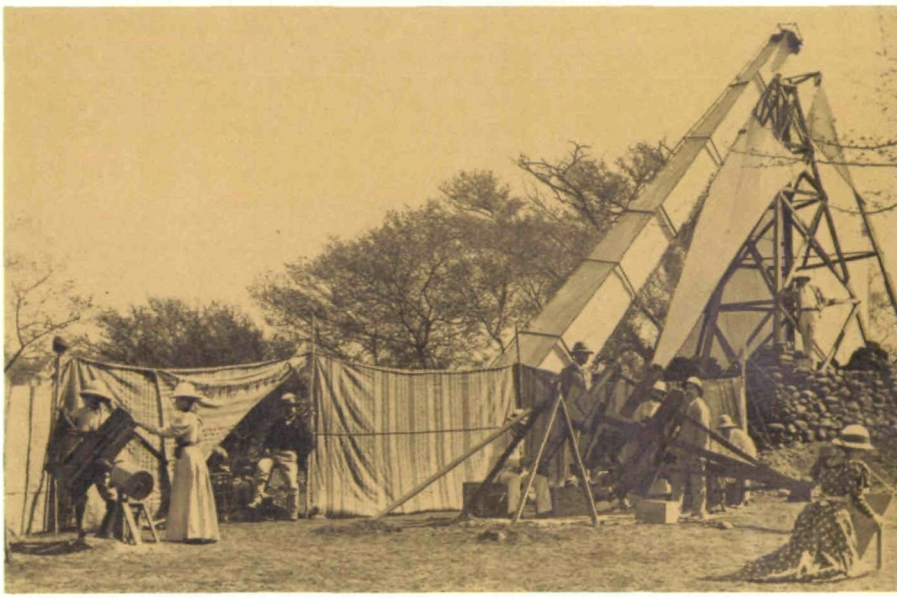
Coronal Photograhs

The first photograph of the corona, a daguerreotype, was taken in 1851 at a total solar eclipse in Poland, but really useful pictures were not secured for another 40 years. The corona is not easily photographed, and most of the early eclipse photographers came home with blank or vastly overexposed plates. The brightness of the corona changes from eclipse to eclipse and there is always a great change in brightness from inner to outer corona. Plates varied and there was never a chance for a test exposure. A major problem in those early years was photography itself, which was only coming of age.

There were marked improvements, year by year, in photo emulsions, and by the 1890's they had improved to where the form of the corona could at last be photographed in detail. A leader in this effort was the Lick Observatory in California, which in 1889 began a dedicated program of coronal photography, which ran for over 40 years.

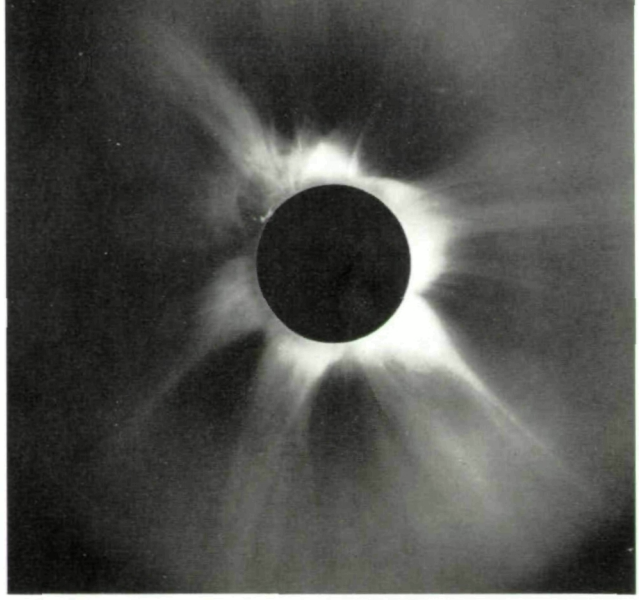
AMERICAN OBSERVERS pose at Burlington, Iowa, following the total solar eclipse of August 7, 1869. Included are two female astronomers, Prof. Maria Mitchell (seated) and Helen Starke, at left. At this important eclipse, Charles Young, seated, near center, discovered the green coronal emission line, which eventually led to our modern understanding of the unique conditions that exist in the corona of the Sun.

EARLY PHOTOGRAPH of the solar corona, made in Shelbyville, Ky., by the Harvard expedition to the total solar eclipse of August 7, 1869. Such pictures are of little value today, for they show only the lowest parts of the corona, and these in poor detail. Early photographers had great difficulty capturing the elusive corona: it was diffuse and ethereal, its brightness varied from eclipse to eclipse, and there were no chances for test exposures. These pictures were made on wet plates, prepared under stress in the field as the sky darkened before eclipse totality. The corona was visible but a few minutes, and the next chance to see it was more than a year later, in Spain.



CORONAL CAMERA, in the days of Queen Victoria. Here the great eclipse telescope of the Lick Observatory, 12-m long, is set up on the plains of India, near Jeur, for the total solar eclipse of January 22, 1898. The great camera, called "Jumbo" by its originator, J. M. Schaeberle, was carried to nearly every total solar eclipse in every continent except Antarctica from 1893 until 1931. It was not guided and had to be pointed ahead of time to the place in the sky where the Sun and Moon would meet. At each eclipse for which skies were clear, it secured about a dozen photographs of the corona, some on glass plates 36 by 56 cm.

In 1893, John M. Schaeberle of the Lick staff developed a special long-focus telescope (or "camera") for photographing the white light corona at eclipse; it was 12 m long and produced images of the Sun and Moon that were 10 cm in diameter. Schaeberle nicknamed it "Jumbo." The giant camera exposed 36- by 56-cm glass plates that were changed by hand by an operator who stood in the dark inside the camera.



SOLAR CORONA, seen in striking beauty at the total solar eclipse of June 8, 1937, on Canton Island in the South Pacific. This portrait, perhaps the best ever taken of the corona, was made by Irving Gardner of the U.S. National Bureau of Standards on a joint expedition with the U.S. Naval Observatory and the National Geographic Society. Towering above the edge of the black Moon we see an unusual prominence, shaped like a bird or dinosaur, nicknamed "Heliosaurus."

From 1893 until 1932 Schaeberle's jumbo camera was taken to nearly every total solar eclipse, on every continent except Antarctica. Each expedition was a major effort requiring the dedication of a significant part of the Lick Observatory staff and resources for about 1 year. In 1893, when Schaeberle took the camera to Chile for an eclipse in April, his voyage started in February and ended in July. Each eclipse expedition not thwarted by weather produced about 10 new pictures of the corona, taken in a span of a few minutes. Some were unsuccessful, as when clouds or drenching rain blocked the Sun during the precious minutes of totality, or when problems beset the instrument at some remote site.

Coronal Physics From Eclipse

Eclipse photographs proved that the corona was part of the Sun, and told much more about it. The corona is made up of radiating rays and streamers with shapes like tulip bulbs, the pointed ends of which stretch out for millions of kilometers into interplanetary space. The form of the corona changes from eclipse to eclipse and evolves in a fairly regular pattern coordinated with the sunspot cycle. At sunspot maximum the corona is complex and crowded with streamers. At sunspot minimum its form is simpler, usually with streamers restricted to the solar equator and with prominent plumelike rays at the solar pole.

Observations of the corona at eclipse established its source, composition, density, temperature, and the relationship between coronal shapes and magnetic field lines rooted in the surface of the Sun.

The faint white light of the corona is really light from the photosphere, scattered by free electrons that make up the actual coronal structures that we see. When we look at coronal streamers and plumes we are seeing patterns of electrons in the corona, made visible because, like motes in a sunbeam, they scatter the light that strikes them. Electrons scatter light without changing its color, and because the photosphere is white, the corona appears white, too.

Because electrons are influenced by magnetic fields, it is not surprising that the structures of the corona resemble magnetic lines of force. The arches and loops that we see in the corona are magnetic arches and looped field lines, along which coronal electrons cluster. The polar plumes resemble patterns taken by iron filings near a bar magnet because coronal electrons, like iron filings, follow the lines of force emanating from the surface magnetic fields near the pole of the Sun. Coronal streamers are bulb-shaped near their bases because they form around closed magnetic arches that connect surface magnetic fields of opposite polarity.

But coronal magnetic fields are strong enough to control coronal electrons to only a limited height above the Sun. At a distance of about 10^6 km, the electrons are free to escape and stream away in what is called the solar wind. Electrons are driven from the Sun, along with protons and other particles, by the heat of expansion of the million-degree corona. The steady flow of the solar wind stretches out the ends of coronal streamers and gives them their long, straight extensions into space.

Limitations of Eclipse Observations of the Corona

Almost all of these concepts have come from eclipses. But observations of the corona at eclipse are limited in two respects. First, because eclipse pictures cover such limited periods in the life of the corona, they cannot show its dynamic changes. The most complete series of eclipse photographs is only a snapshot album, with long time gaps of a year and more between one set of pictures and the next. Second, eclipse pictures cannot reveal the three-dimensional shape of coronal forms because photographs show the corona always in two dimen-

sions, as though projected against the screen of the sky. They cannot tell whether coronal structures are flat or circular in cross section. They cannot tell whether a coronal streamer points obliquely toward Earth or away from it, a question important in tracking its possible influence on Earth. Nor is it possible to determine how features in the corona are related to prominences and flares and other surface activity.

Efforts were made, from the time of the first drawings and first photographs, to search for changes in the corona that might by chance take place during the short time when the Sun was totally eclipsed. In 1905 the Lick Observatory attempted this by building two additional jumbo cameras, copies of Schaeberle's original, and setting them up along the path of totality. For the eclipse of that year one was built in Labrador, one in Spain, and one in Egypt, beside the Nile at Aswan. The time of totality at each station was about 3 min. Totality occurred first at Labrador, about 90 min later in Spain, and still an hour later in Egypt. The results of this ambitious experiment were typical of other such efforts before and since. The Labrador station did not see the corona because of heavy overcast; the sky was hazy in Spain, though adequate for photos, and worse in Egypt, where a desert sandstorm left the sky bright and the plates poor. A careful comparison of Spanish and Egyptian plates revealed no perceptible changes in the corona over a period of 1 hr.

The same experiment had been tried earlier, and at nearly every subsequent eclipse. Movies of the corona are almost always made at eclipse and are studied frame by frame for possible fast changes during the minutes of totality. In all these studies, there were only a few cases of possible subtle changes, as in the orientation of a polar plume or a slight shift in a streamer, but no clear evidence of the dynamic alteration of coronal form that was suspected to result from dynamic surface events. If changes on the surface of the Sun are to be associated with changes on Earth, we need observations of the media between, which includes the passage of these events through the corona.

The one and only hope of detecting changes in the corona, and in answering the questions of its three-dimensional form, depended upon the invention of an instrument that can see the corona when the Sun is not eclipsed. It was obvious to most that this could only be done on a high mountain, where the sky was dark; many mountaintops were tried. For over 60 years the search went on in many ways and in many lands, for a workable coronagraph, but without the slightest shred of success.

THROUGH THE CORONAGRAPH

In the summer of 1930 the French astronomer Bernard Lyot succeeded in developing the contrivance that so many had desired for so long. His coronagraph was a simple device: a telescope in which the image of the photosphere was blocked by a small metal occulting disk, which served as a miniature Moon. Lenses behind the occulting disk focused the corona in an eyepiece, in a spectrograph, or on film.

These same techniques had been tried by others, long before Bernard Lyot was born. He applied nothing new, except patience, perseverance, and meticulous care. With optical baffles and apertures he reduced the stray light that was scattered in lenses and other parts of the coronagraph. He carried his instrument through the snow to the top of the highest mountain that he could effectively employ, the Pic du Midi, 2680 m above sea level in the French Pyrenees. Lyot's coronagraph was over 6 m long, but he had designed it so that it could be carried on the back of a man. It was made of collapsible aluminum tubing and weighed but 49 lb.

Early Coronagraph Results

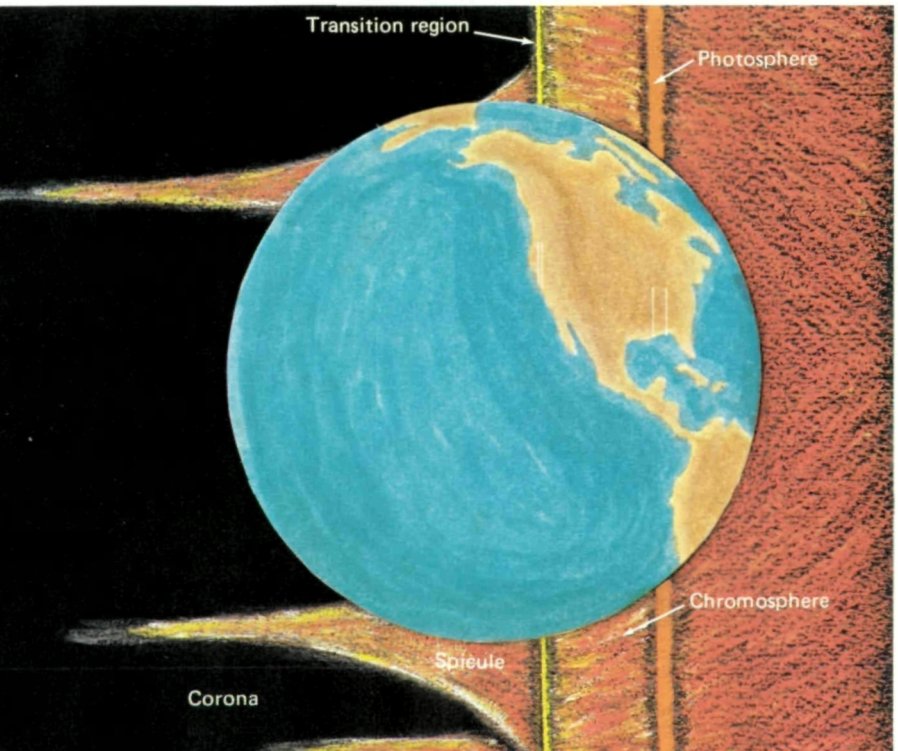
Lyot's first pictures of the corona, to those who expected to see it as at natural eclipse, were surely disappointing. With his first coronagraph, in fact, he could not even see the continuum, or white light corona. But with a spectroscope attached to the coronagraph, Lyot could suppress the bright sky background enough to observe the spectrum of the brightest emission lines coming from the inner corona near the edge of the Sun. From the Pic du Midi he saw the coronal lines that others had glimpsed only at eclipse. He could study them more intensively, and set his camera for long exposures—some for half a day. With these long exposures Lyot discovered new coronal lines in the visible and near-infrared spectrum, and learned many important details and relationships of the emission-line corona.

Lyot's coronagraph could see only the innermost corona—as could other ground-based coronagraphs built on his design. They could observe, with the aid of the spectrograph, the lower parts of

the coronal structures seen at eclipse, a narrow band just above the chromosphere. But these data provided the facts and numbers that led to the first understanding of the physics of the corona as a whole. His coronagraph spectra made possible the identification of the source of the coronal lines. They come from very highly ionized but common elements, ending an embarrassing enigma that had troubled astronomy for 70 years, and revealing a dramatic temperature increase in the outer solar atmosphere.

In time, more sophisticated versions of Lyot's coronagraph were developed, including those that took advantage of the polarization of coronal radiation to detect the white light form. These instruments show the shape and density and some changes in the corona, although they are limited by generally coarse spatial resolution and are generally restricted to the lower corona. Coronagraphs supplement eclipse observations of the corona, but they have never supplanted them because they can never really duplicate the unique observing conditions available at the time of a natural eclipse. No ground-based coronagraph has ever produced a picture of the corona that shows the exquisite form and detail that we see with the naked eye during a total solar eclipse.

OUR TINY PLANET EARTH serves as a yardstick to scale the thickness of the layers of the solar atmosphere. The photosphere (orange layer), where sunspots are formed, is about as thick as Alabama is wide—about 400 km. The less dense and more turbulent chromosphere (red-orange) spans several thousand kilometers, stretching on our scale from Alabama to Los Angeles. The intensely active transition region (yellow), first observed in detail by Skylab, is very thin—equal in width to metropolitan Los Angeles. Spicules (red) extend the chromosphere into the corona as pointed waves whose heights are roughly equal to Earth's diameter. Prominences (not shown) and the corona (black) reach far into interplanetary space, and are much too large for our terrestrial scale.



The reason for this limitation is the light of the sky. At eclipse we see the corona as at night, against a sky so dark that stars appear. With the coronagraph, we look at the Sun in daylight—against a bright sky background that, near the Sun, is particularly intense. The brightness of the sky near the Sun depends upon the altitude and upon the amount of pollutants present in the air, both natural and manmade. The higher and cleaner the air, the darker the sky and the better we can detect the faint corona with a coronagraph. On the Pic du Midi, Lyot demonstrated that in clean, cold air of the Pyrenees the daytime sky is dark enough that one can detect the corona to a distance of a few minutes of arc above the limb of the Sun, or to about 1.3 solar radii from the center of the disk. Subsequent developments in ground-based coronagraphs have extended this, under the best conditions, to about 2 solar radii. At natural eclipse, by contrast, it is possible to observe the corona with a simple telescope or the naked eye to 5 or 6 solar radii, and sometimes farther.

Coronagraphs above Earth

In the 1940's and 1950's, attempts were made to carry a coronagraph above the tops of mountains, in high-flying aircraft and manned balloons. The attempts were not very successful, in part because the brightness of the high-altitude sky was not well known at that time and because the coronagraphs used were only exploratory models. But they brought about an important improvement in the Lyot coronagraph, which was first developed by John W. Evans for aircraft use. He recognized that the Lyot coronagraph was limited by instrument-scattered light, and that this scattered light must be further reduced for a coronagraph to take advantage of skies darker than those at mountaintop. Evans added an extra external occulting disk mounted on a long stem in front of the first coronagraph lens. The added disk shaded the lens, when properly pointed, from direct sunlight. The external occulting disk reduces the scattered light in the coronagraph very significantly, but it does it at the expense of restricting the view. This type of coronagraph can see only the outer parts of the corona.

The early efforts with aircraft and manned balloons paved the way for more sophisticated and more successful flights in the 1960's and 1970's, including the use of coronagraphs in rockets and on two of the NASA Orbiting Solar Observatory (OSO) spacecraft, in programs of the U.S. Naval Research Laboratory (NRL). The NRL coronagraph on OSO-7 observed, soon after launch, a dramatic transient disturbance in the corona that seemed to be expelled from the Sun into interplanetary space. It was the first time that such an event had been recognized in the corona in white light, and the culmination of a search that had been pursued for more than a century. The same instrument observed a number of subsequent events, setting the stage for a more intensive and detailed study of coronal transients by a larger and more sophisticated coronagraph on Skylab.

The Sun's Vital Statistics

Age	At least 4.5 billion years, in present state
Distance:	
Mean distance from Earth	1.5×10^8 km
Variation in distance through the year	±1.5 percent
Diameter	1.39×10^6 km (or 109 times the diameter of Earth and 9.75 times the diameter of Jupiter, the largest planet)
Volume	1.41×10^{33} cm^3 (or 1.3 million times the volume of Earth)
Mass	1.99×10^{30} kg (or 333 000 times the weight of Earth
Magnetic field strengths (typical):	
Sunspots	3000 G
Polar field	1 G
Bright, chromospheric network	25 G
Emphemeral (unipolar) active regions	20 G
Chromospheric plages	200 G
Prominences	10 to 100 G
Earth (for comparison)	0.7 G at pole
Chemical composition of photosphere (by weight, in percent):	
Hydrogen	73.46
Helium	24.85
Oxygen	.77
Carbon	.29
Iron	.16
Neon	.12
Nitrogen	.09
Silicon	.07
Magnesium	.05
Sulfur	.04
Other	.10
Density (water = 1):	
Mean density of entire Sun	1.41 g/cm^3
Interior (center of Sun)	160 g/cm^3
Surface (photosphere)	10^{-9} g/cm^3
Chromosphere	10^{-12} g/cm^3
Low corona	10^{-16} g/cm^3
Sea level atmosphere of Earth (for comparison)	10^{-3} g/cm^3
Solar radiation:	
Entire Sun	3.83×10^{23} kW
Unit area of surface of Sun	6.29×10^4 kW/m^2
Received at top of Earth's atmosphere	0.136 W/cm^2
Surface brightness of the Sun (photosphere):	
Compared to full Moon	398 000 times
Compared to inner corona	300 000 times
Compared to outer corona	10^{10} times
Compared to daytime sky on Pikes Peak	100 000 times
Compared to daytime sky at Orange, N.J.	1000 times
Temperature:	
Interior (center)	15 000 000 K
Surface (photosphere)	6050 K
Sunspot umbra (typical)	4240 K
Penumbra (typical)	5680 K
Chromosphere	4300 to 50 000 K
Corona	800 000 to 3 000 000 K
Rotation (as seen from Earth):	
Of solar equator	26.8 days
At solar latitude 30°	28.2 days
At solar latitude 60°	30.8 days
At solar latitude 75°	31.8 days

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3
The Sun From Space

We live at the bottom of a deep ocean of air, and therefore every object outside the Earth can be seen by us only as it looks when viewed through this great depth of air. Professor Langley has shown recently that the air mars, colors, distorts, and therefore misleads and cheats us to an extent much greater than was supposed.

—William Huggins, 1885

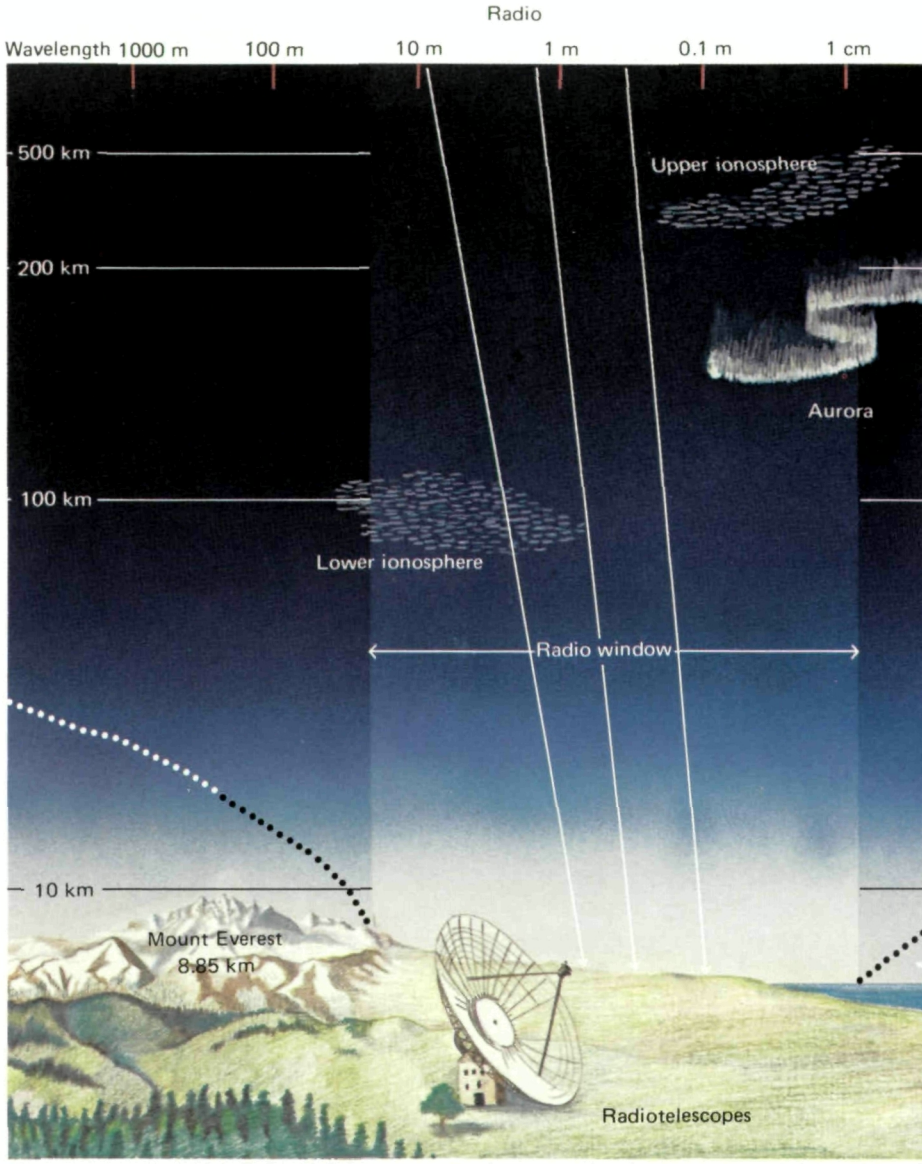
In the chapter preceding we looked at the masks of the Sun and the ways we see them: the photosphere in white light, the chromosphere with the spectrograph and spectroheliograph, the corona at eclipse and with coronagraphs, and the magnetic field with a spectrograph-magnetograph. Each method was developed to observe the Sun from the surface of Earth, and in varying degree, each is limited by the ocean of air that lies above.

It was to reduce the effect of the ocean of air that Lyot carried his coronagraph to the summit of the Pic du Midi, and why most solar observatories are built on mountaintops. Astronomers have long known that the ideal observing site lies above the dense and dirty ocean of air, and as methods have been developed to rise above the atmosphere, solar astronomers have been quick to put them to use. Astronomical apparatus was carried aloft in early balloon ascents in the 18th century. Solar and galactic cosmic rays were studied from instrumented balloons in 1911. As early as 1923, astronomers climbed into the open cockpits of aeroplanes to observe a total solar eclipse from above the clouds. In 1935, when the National Geographic Society and U.S. Army sent the manned balloon Explorer II to a record height of 22 km, instruments were on board to measure the solar spectrum. When instrumented rockets came to science at the end of World War II, solar physicists were waiting to put them to use in exploring the unseen ultraviolet and X-ray radiation of the Sun. In keeping with this tradition, the first sophisticated unmanned satellites were dedicated to solar observation—the eight highly successful Orbiting Solar Observatories, which have kept watch on the Sun for more than the 11-year solar activity cycle, from 1961 through 1978. On Skylab, the world's first long-term orbital laboratory, solar observation took much of the budgets of space, weight, and time.

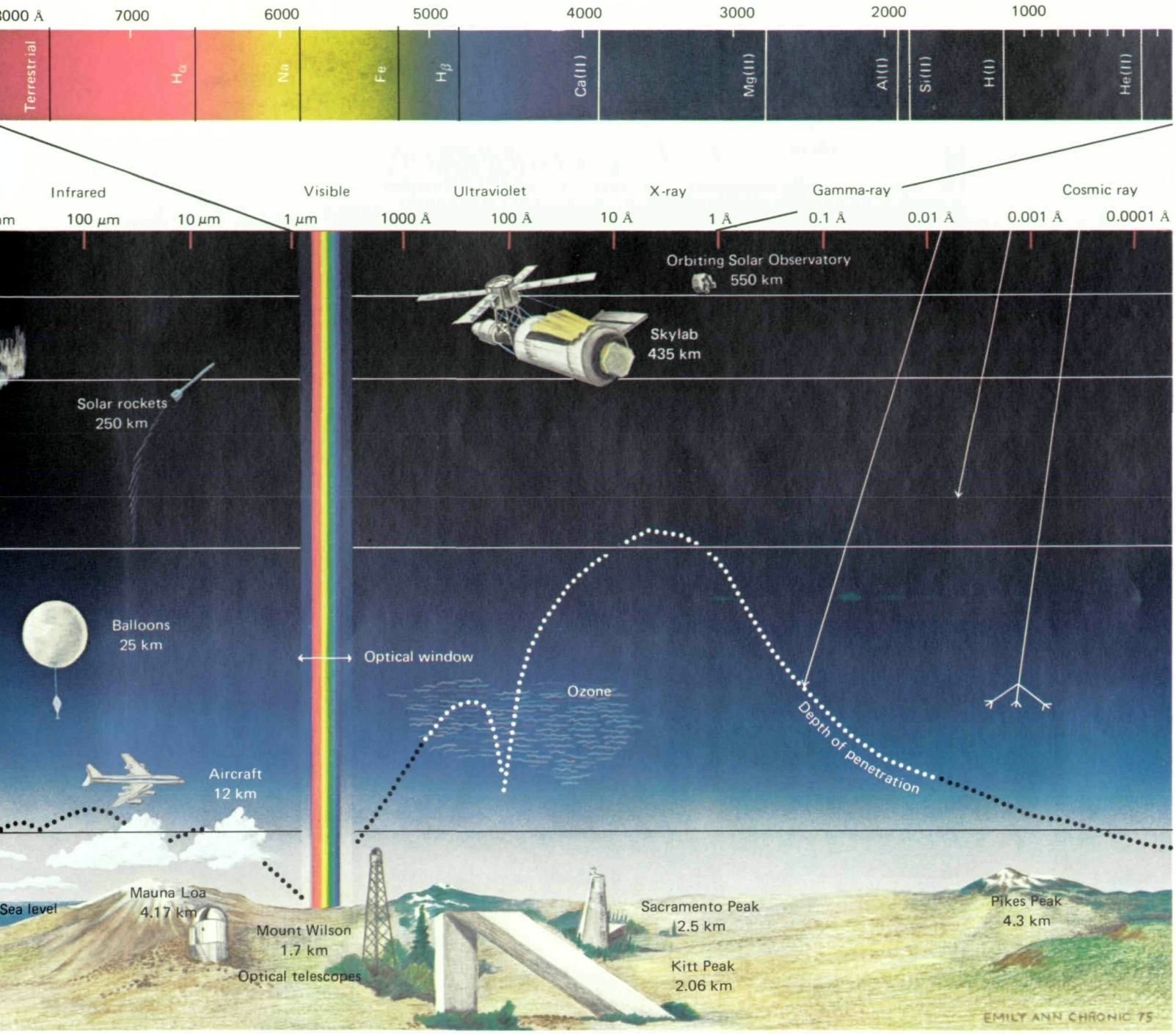
TRANSMISSION OF THE ATMOSPHERE

The first and most important reason for ascending above the atmosphere is to push back the limits of the solar spectrum that can be seen and studied. At the surface of Earth, we receive only part of the solar radiation that strikes the top of our atmosphere. The ocean of atmosphere acts like a filter, letting certain wavelengths pass but screening others, some completely. Most of the light in the visible part of the spectrum passes through our atmosphere unabsorbed, but the shorter (ultraviolet and X-ray) and longer (infrared) wavelengths are selectively absorbed by various gases in the upper atmosphere. If we point a ground-based telescope at the Sun and record its complete spectrum, from one end of the wavelength scale to the other, we will find our spectrogram almost blank for wave-

Solar spectrum viewed by Skylab instruments showing principal absorption and emission lines



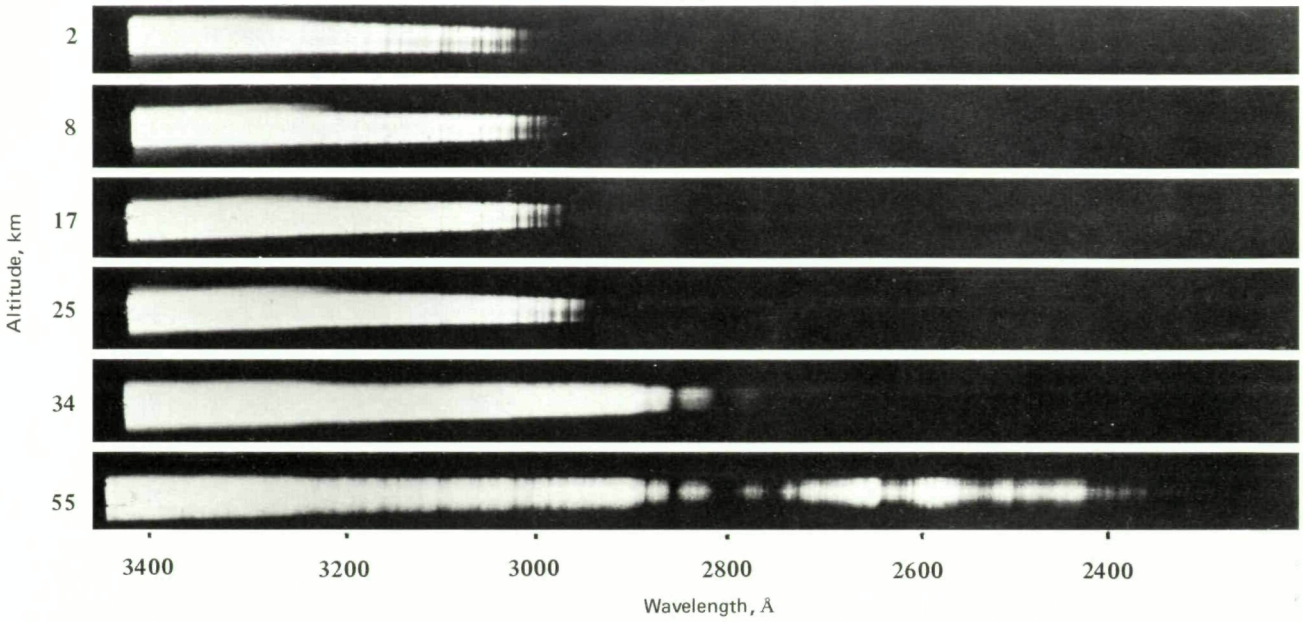
SPECTRUM OF SOLAR RADIATION. Visible sunlight is but one part of the total radiation Earth receives from the Sun; shown here is the full span of electromagnetic radiation from our nearest star. Electromagnetic radiation such as sunlight travels in waves, the wavelengths of which serve as descriptions, or identifiers, of the different forms of radiation. Our eyes see only a narrow band of wavelengths—the "visible spectrum" of rainbow colors from about 4000 to 7000 Å, violet to red. We see it on the chart as a rainbow of colors. To the left of the visible spectrum is the infrared, covering a wider band of wavelengths, reaching from the red of the visible to wavelengths of about 1 mm. The Sun emits light, or radiation, throughout this region. Although we cannot see it, we can feel infrared waves as heat on our skin. To the left of the infrared stretches the vast spectrum of radio wavelengths, where the Sun also emits energy that



is detectable by solar radio telescopes that "hear" it on radio receivers as a form of cosmic static. To the right of the visible spectrum stretch the shorter and more energetic wavelengths of ultraviolet radiation, X-rays, gamma rays, and cosmic rays. All are invisible to our eye. These shorter, invisible wavelengths arise in the upper, more active layers of the Sun, and are thus especially valuable for the study of the active Sun. Special telescopes and sensors are required to measure the radiation at these wavelengths.

The atmosphere of Earth is transparent to visible sunlight; almost all the sunlight in the visible spectrum passes through the air to reach the surface of the ground. Gases in the terrestrial atmosphere, such as oxygen, ozone, or water vapor, absorb most of the infrared, ultraviolet, X-ray, and shorter wavelengths of solar radiation before it reaches us. On the chart Earth's atmosphere is shown in vertical cross section, with a scale of height above sea-level at left. The depth to which each region of the solar spectrum penetrates is shown as a dotted line. In the radio region, like the visible, penetration is almost complete, and these regions are called "windows." X-ray radiation is totally absorbed far above Earth, at an altitude of about 100 km. Skylab, and other spacecraft and rockets, were at altitudes high enough to feel and observe the full range of electromagnetic radiation from the Sun—a feat impossible for solar astronomers on the ground.

Skylab carried special telescopes to observe the Sun in the region from about 2 to 7000 Å wavelength, in X-ray, ultraviolet, and visible regions of the spectrum. Its region of observation is shown in the expanded spectrum at the top, with spectral lines of special interest as dark, vertical lines.



FIRST PHOTOGRAPHS OF THE ULTRAVIOLET SPECTRUM OF THE SUN, made from a V-2 rocket on October 10, 1946, under the direction of Richard L. Tousey of the U.S. Naval Research Laboratory. A sequence of exposures shows how more and more of the ultraviolet radiation of the Sun is recorded as the rocket rises in altitude from 2 to 55 km above sea level.

lengths shorter than violet and longer than red. If we take the same instrument aloft, in a rocket or satellite, we will find the same spectral region covered with intense emission lines and a strong and variable continuum.

These nonvisible parts of the solar spectrum are important because they originate in the Sun's most active layers: the upper chromosphere, the corona, and the region of transition between. These regions radiate most of their energy in the ultraviolet and X-ray wavelengths, as do solar flares. Thus if we "look" at the Sun in these wavelength regions we "see" these layers and these features with great advantage. A spectroheliograph that operates in the ultraviolet region of the spectrum can make full disk pictures of chromospheric layers that cannot be seen in other ways. In the far ultraviolet it can record the otherwise unseen transition region in all its detail over the full disk of the Sun. Because very little X-ray emission comes from the underlying photosphere, an X-ray telescope can make pictures of the corona, not just at the limb of the Sun as at eclipse or with a visible coronagraph, but over the entire disk.

These possibilities offer tremendous advantages over ground-based visible light observation. They offer views of the layers and processes that hold the keys to many of the secrets of the Sun.

We have been able to observe the Sun in detail in these regions for only about two decades. But in the 20 years we have learned more of the Sun than at anytime since the invention of the telescope.

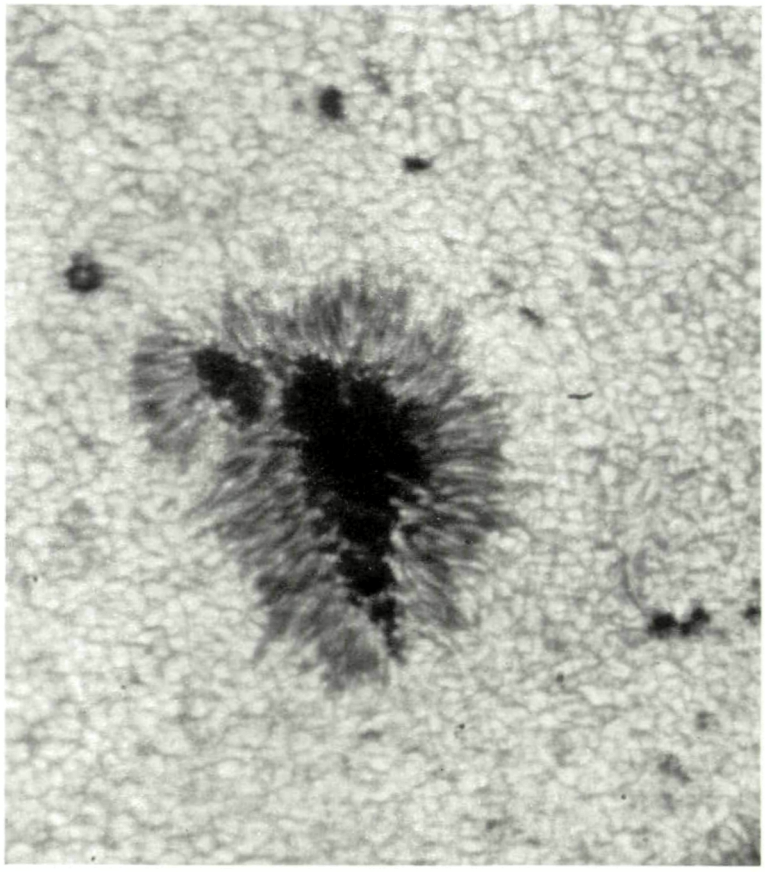
IMAGE DISTORTION

A second advantage in rising above Earth's atmosphere is improved image steadiness, or "seeing." Light rays from the Sun are distorted and bent by changes in the temperature and density as they pass downward through the ocean of air. These distortions make stars twinkle when seen with the naked eye and dance about in the eyepiece of a telescope. They blur an extended object like the Sun, because rays from different parts of it are

THE DISTORTING EFFECT of the atmosphere is evident in these photographs of moonset, made from above Earth on Skylab. A white cloud deck covers the surface of Earth; above it, but beneath the spacecraft, the ocean of air spreads like a light blue blanket. The Moon lies far beyond. In the first photo the Moon is seen undistorted against the black sky of space. In the succeeding pictures the Moon flattens and blurs as it sets behind the ocean of air. Observers on the ground must look at celestial objects from beneath the ocean of air and make allowances for the distortions that we see here in exaggerated form.

distorted in different ways. Atmospheric distortions cheat all astronomers, but they are worse in the daytime when temperature gradients and fluctuations are most severe. Even on bright clear days, atmospheric distortion can blur most of the detail from the solar image, leaving only the largest features. In typical observation, the solar limb appears to boil and seethe, as projected in a telescope.

Certain atmospheric conditions are conducive to good seeing, and astronomers have attempted to locate their telescopes in areas where these conditions are most frequently met. These are not always at high altitude—some mountain locations have poor seeing, and there are places at sea level where excellent image steadiness is often found. As a rule, however, the most dramatic improvements



A CLEAR LOOK at the surface of the Sun, made from the Stratoscope I balloon telescope at an altitude of 24 000 m on August 17, 1959. At that altitude the 25-cm automated telescope was above most of the turbulent parts of the atmosphere, where it could see details of sunspots and the photospheric granulation with clarity rarely found on the ground. The smallest granules seen, at the limiting resolution of the telescope, are about 320 km across—the size of many eastern States in the United States. The largest areas are as big as Mexico. The sunspot at center is twice as large as Earth.

in daytime seeing come with altitude. This was impressively demonstrated by Martin Schwarzschild and his colleagues of the Princeton Observatory who, in a series of pioneering unmanned balloon flights in 1957 and 1959, sent an automated 25 cm telescope aloft to photograph extremely fine details of photospheric granulation and sunspots.

SKY BRIGHTNESS

A third advantage is a darker sky, which is of great benefit to coronal observation. In chapter 2 we found how coronagraphs are limited by the background sky brightness and how this is overcome in part by climbing to thinner air and darker skies. The deep blue skies of the mountains are a part of their striking beauty and appeal; in the mountains the Sun looks whiter and the shadows sharper and darker. On the clearest days on high mountains the sky looks blue-black, but even then it is still brighter by far than the corona, except at the very edge of the Sun. A coronagraph on a mountaintop must wait for these clearest days to see the corona really well, and even then it has to pick it out against a background "glare" as bright as the corona itself. The outer corona, several hundred times dimmer, is unobservable from mountaintops with present coronagraphs.

At balloon altitudes of 25 to 30 km (six times higher than mountaintop observatories) the sky in the visible region of the spectrum is nearly 100 times darker, but even there the sky is so bright that most of the outer corona cannot be seen. At an altitude of about 50 km above sea level the daytime sky is as dark as that seen on Earth during a total eclipse, which still limits practical observation of the corona to 5 or 6 solar radii. At satellite altitudes of 200 to 400 km, so little air remains that the daytime sky near the Sun is truly black, offering no limit to observation of the faintest details of the white light corona.

CONTINUOUS PATROL

A fourth and final advantage in extraterrestrial observation of the Sun is freedom from clouds and the interruption of the long terrestrial night. Many of the important questions of the Sun—especially those that deal with solar activity and change—require a more or less continuous patrol of the solar surface for their ultimate answers. This was the basis for an extensive collaboration of world solar observatories during the 1957-58 International Geophysical Year. During that time efforts were made to keep a coordinated and continuous patrol of the Sun by the organized cooperation of a chain of solar observatories around the world. As the Sun set on solar telescopes in southwestern United States, it was kept in view by stations farther west—in California and Hawaii and then Japan and later India, the Soviet Union, and the countries of Western Europe. The afternoon solar patrol in Europe was overlapped by the morning watch of the Sun in America, and so on.

This system is kept up today, informally, be-

cause solar observatories around the world cooperate and share their data fully. But problems of two sorts make this worldwide chain of surface stations less than perfect. The first is meteorological. Key stations, or sometimes all stations, can be blocked from seeing the Sun by persistent weather patterns, resulting in long data gaps. In addition, subtle differences in sky conditions from station to station make the combined data patchy and nonuniform. The second problem is instrumental. Different instruments at diverse stations around the world are not alike and are not uniformly calibrated. Different observing procedures, and even different observers, portray a slightly different Sun. Even the simple matter of recording the number of sunspots on the Sun requires individual correction factors for specific telescopes and operators to be brought into agreement. For some problems these differences are not important; but for others they are crucial.

A single telescope in orbit around Earth can keep a nearly continuous watch on the Sun—a procedure that offers many advantages, including economy. The data are uniform and uniformly good. There are no clouds or other variations in the background sky; it is always clear and monotonously black. Observations are interrupted only when the spacecraft moves across the night side of Earth, but the spacecraft night is short. In the most unfavorable orbit the cycle for an Earth-orbiting spacecraft is about a 45-min day, followed by a 45-min night. In more polar orbits the Sun can be watched continuously for much longer periods with instruments that are always "on station and ready."

Skylab brought together, in a single orbiting observatory, solar instruments to capitalize on each of the advantages of observation above Earth. Three sophisticated solar spectrographs watched the Sun in the full span of the ultraviolet, with almost no absorption between their apertures and the Sun itself. Two X-ray telescopes brought to focus the full and unattenuated X-radiation of the Sun. White light and H_α telescopes kept a constant patrol of the Sun through the clear and steady vacuum of space, unhindered by vacillating currents and clouds in the ocean of air beneath them. An Evans white light coronagraph took continuous pictures of the corona against a background of black sky. For 251 days and nights Skylab kept its arsenal of telescopes directed at the Sun from a vantage point 435 km above the surface of Earth.

ON STATION AND READY, Skylab floats against a black daytime sky, ready to take on board her third and final crew. The Apollo Telescope Mount and its four solar power panels face the Sun above. During EVA, astronauts climbed to the circular disk to replace camera film magazines. The solar telescope array was controlled during manned operation from within the multiple docking adapter, the cylindrical structure marked by a flag near the round entrance door. During periods between manned operations of Skylab, some of the solar telescopes were controlled remotely by radio command from the NASA Johnson Space Center in Houston, Tex.

4
The Solar Telescopes on Skylab

The heat and light of the Sun are so intense that peculiar instruments and methods are necessary for the observation of his surface. The appliances used in the study of the moon, planets, and stars will not answer at all for solar work.

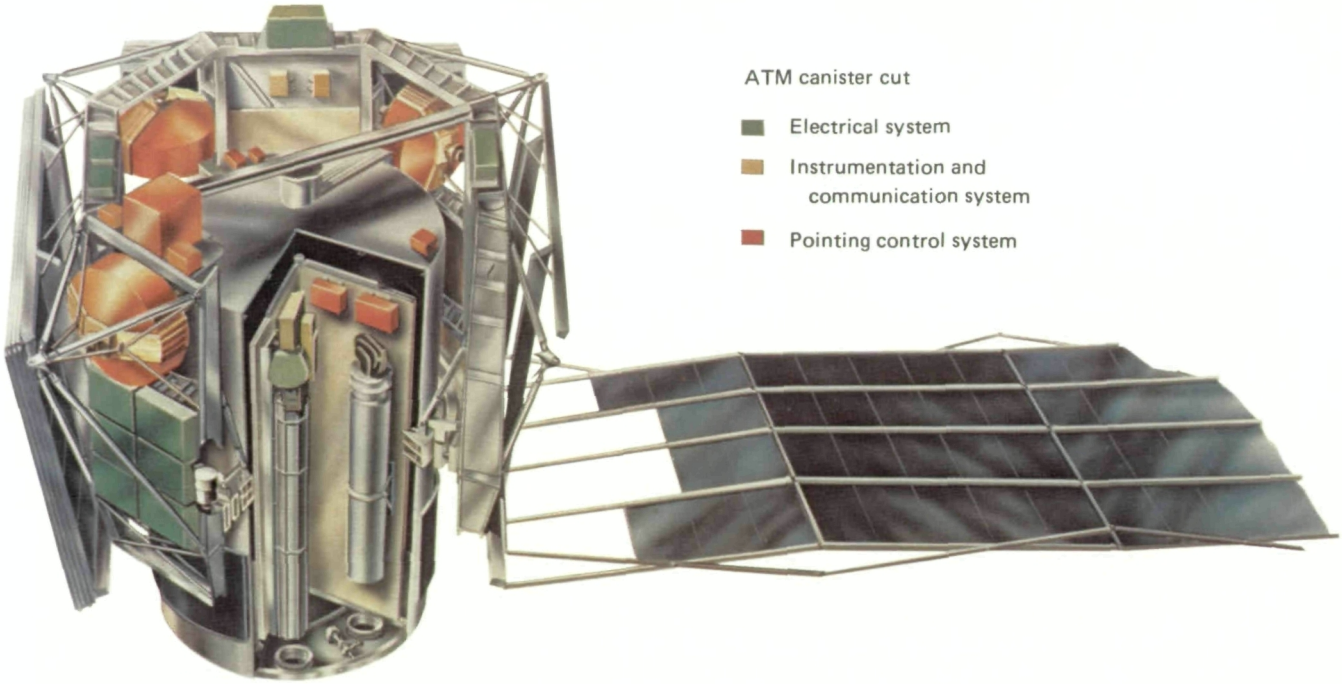
—Charles A. Young, 1896

The Apollo Telescope Mount (ATM) on Skylab was this country's first full-scale, manned astronomical observatory in space. Many unmanned astronomical spacecraft had preceded it, including the highly sophisticated and successful Explorer, Mariner, Pioneer, Orbiting Astronomical Observatory, and Orbiting Solar Observatory (OSO) spacecraft series. The manned Mercury, Gemini, and Apollo missions carried astronomical apparatus, which was employed with good results by astronauts, but none of these instruments approached the size and overall capability of the battery of solar telescopes that made up the ATM.

The predecessor of the ATM in observing the Sun from space was a series of seven unmanned OSO's. Like the Skylab ATM, the OSO's were designed for about 1 year's use, circled Earth in a little over 90 min, and sent data to the ground by many of the same radiotelemetry stations that were used by Skylab. Like Skylab, each OSO carried an array of solar instruments, from rudimentary counting devices that measured radiation from the whole Sun, to pointed telescopes for ultraviolet, X-ray, and coronagraphic observation of specific parts and regions of the Sun. But solar instruments on the early OSO's were limited in size and weight and by restricted power and telemetry budgets. The largest solar instruments on the pre-Skylab OSO's were about 1 m long, weighed less than 25 kg, and worked with power budgets of a few watts. Data storage and telemetry created severe limitations. Total spacecraft weight was about 275 kg, of which about half was allotted to solar instruments.

Skylab, by comparison, was bigger than a boxcar and weighed over 90 000 kg. The ATM experiment canister, which housed the eight principal solar telescopes, was 3 m long and over 2 m in diameter—as large as any modern solar observatory spar on Earth, and it was pointed at the Sun with an accuracy and steadiness that equaled the performance of an observatory telescope on the ground. The solar telescopes on the ATM were not miniature models but full-sized observatory instruments, typically 3 m long and weighing, in all, more than 900 kg. They had virtually no power restrictions. The solar experiments on Skylab had their own source of power, derived from photovoltaic cells that covered four large vanes stretched out like giant windmill blades. The system was capable of delivering over 2000 W of experiment power, as compared with about 20 W on the last pre-Skylab OSO.

Just as important, the ATM had vast capabilities for recording and storing solar data, made possible, chiefly, through the use of photographic film. The luxury of film is denied most unmanned space experiments because of the difficulty of returning film or photographic images to Earth. Thus, previous solar spacecraft were obliged to replace cameras with photoelectric sensors used to transmit obser-

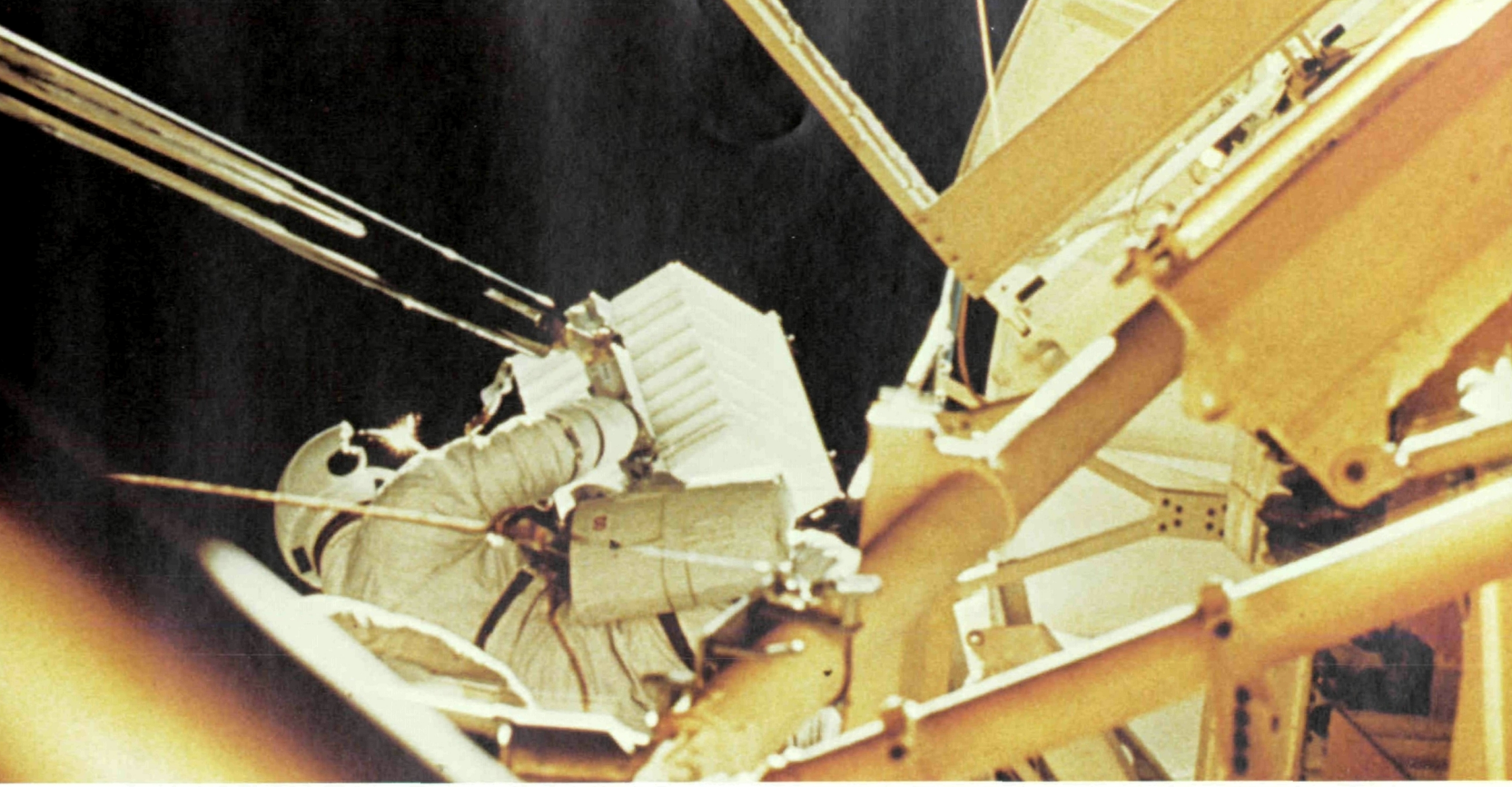


AN ARTIST'S CONCEPT OF THE ATM SOLAR OBSERVATORY reveals the inside of the experiments package. Eight solar instruments were contained in the cylindrical enclosure to provide protection against severe temperature excursions and any residual contamination as the spacecraft orbited Earth. The entire canister was supported on gimbals to allow precision pointing and stability while gathering data on various solar features.

vational data to ground by radio telemetry. A single "picture" of the Sun, for instance, is divided into perhaps a million pieces, or "bits," which are transmitted, one by one, by radio signals. For a spacecraft that orbits Earth, these transmissions can be made only during certain limited times—when the spacecraft is within line-of-sight radio range of special ground receivers. As a result, the telemetry system is often a bottleneck in space observations.

Because Skylab was manned by visiting astronaut teams, it was possible to employ film in ATM cameras. This film was then brought back to the surface of Earth by returning astronaut crews. Photographic film provides a fast and efficient way of recording and storing images, and for most of Skylab's solar instruments, film was used. The Skylab astronauts retrieved and replaced film in ATM instruments by extravehicular activity (EVA), using film magazines especially designed for this unorthodox loading and unloading procedure. Although their principles of operation and replacement were much the same, ATM film magazines were a good deal bulkier than the instamatic cartridges used in most cameras. Some ATM camera magazines held film for 16 000 pictures or "frames"; others advanced film in strips and weighed, on Earth, over 40 kg. Film magazines adequate for the entire Skylab mission were stored in lockers in the Skylab Orbital Workshop when it was launched to start the mission on May 14, 1973. Extra magazines were added to the final extended mission and were transported in a crowded command module at the time of launch in November. On board each Apollo command module that splashed into the Pacific were several exposed film magazines, which were rushed to waiting ATM scientists for development and processing.

In all, nearly 30 of the special film canisters were loaded, exposed, and returned to Earth from



ATOP THE APOLLO TELESCOPE MOUNT Astronaut Owen Garriott removes a film magazine (white box) from one of Skylab's solar telescopes during an EVA in the second manned Skylab mission. A long boom transports it back to the waiting hands of another crewmember at the airlock door below. During the operation, Garriott, film, boom, and Skylab were 435 km high, speeding around Earth at 29 000 km/hr. But because they moved together, and with no wind resistance, there was little sense of motion.

the six ATM experiments that used film; over 150 000 successful exposures were obtained. Solar film from ATM cameras was the heaviest and largest item on each packing list of materials brought back from Skylab in each returning command module.

DESCRIPTION

The ATM was an instrument rack and protective canister that held Skylab's array of solar telescopes and kept them pointed at the Sun. It served the same purpose as a solar-guided spar in an earth-bound solar observatory on which several solar telescopes are attached for pointing at the Sun. During launch, the ATM was positioned on top of Skylab and in line with it at the most forward point under the pointed, protective rocket shroud. After the spacecraft was in orbit and the shroud was jettisoned, the ATM was swung into working position by rotation outward through 90°, locking into place at right angles to the main axis of Skylab. Then, four solar power panels were unfolded, exposing their photovoltaic surfaces to the direct light of the Sun from which they derived electric power. Photoelectric Sun seekers on the sunward face of the ATM canister provided error signals to large gyroscopes and actuators that were used to keep the entire ATM pointed at the Sun to the almost unbelievable tolerance of ± 2 arcsec—an angular error of no more than the width of a dime at a distance of about 2 km. A small, star-seeking telescope on the ATM was added to look at a second star, Canopus, in the southern sky, to provide additional information for overall spacecraft orientation.

Within the ATM experiment canister was a rigid beam, cruciform in cross-section and about 3 m long. This was the spar or optical bench on which the solar telescopes were mounted. On the front (sunward) end was a sunshield and cover, with openings and individual doors for each instrument. During ground storage, launch, and at times when orbital contamination was expected, these experiment doors were closed to protect the solar instruments and their optical components.

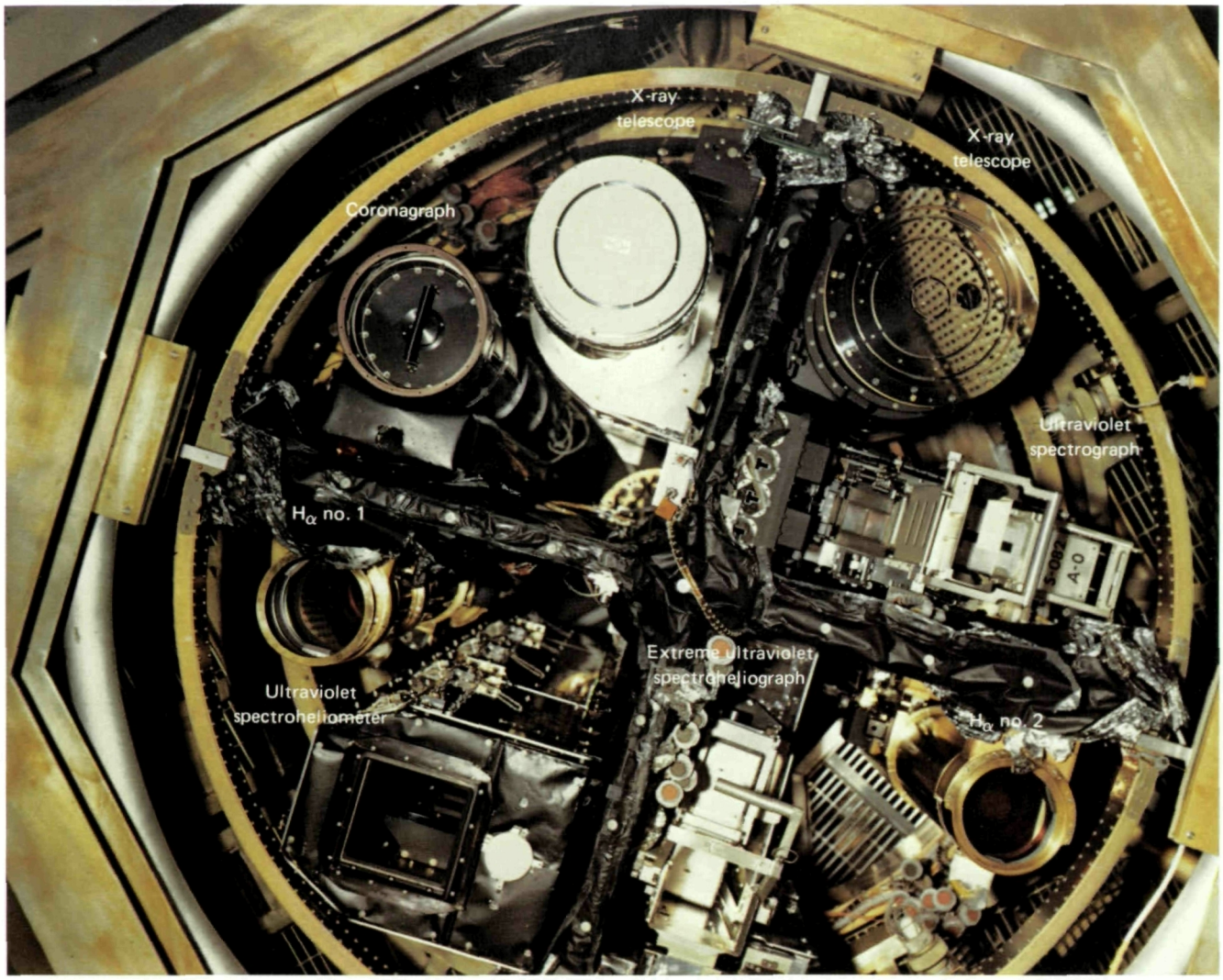
MASSIVE ON EARTH, but weightless in space, one of Skylab's solar telescopes is prepared for final assembly in the ATM canister, 21 months before launch. Technicians in special clean room clothing make final checks on the Naval Research Laboratory ultraviolet spectroheliometer at the Marshall Space Flight Center in August 1971. Fastidious care and engineering skill resulted in near-perfect operation of all of Skylab's solar instruments, and in a harvest of scientific results that exceeded all expectations.

SOLAR INSTRUMENTS ON SKYLAB

Eight separate solar telescopes were mounted on the ATM spar. The six principal instruments were two X-ray telescopes, an extreme ultraviolet spectroheliograph, an ultraviolet spectroheliometer, an ultraviolet spectrograph, and a visible light coronagraph. Together they collected data on the Sun in wavelengths from 2 to 7000 Å which spanned the soft X-ray, ultraviolet, and visible light ranges of the electromagnetic spectrum. Each was the most advanced instrument of its type ever to be flown in space, and each took full advantage of the unique conditions of Skylab's orbit. None would have served any purpose on the ground or in a mountain-top observatory. The X-ray and ultraviolet instruments, covering the wavelength span from 2 Å to the violet edge of the visible spectrum, needed the altitude of Skylab's orbit to get above the complete atmospheric absorption of radiation in these regions. The coronagraph took advantage of the negligible sky brightness at Skylab's altitude.

All eight ATM solar experiments are described in the following sections, along with a ninth Skylab solar experiment, a handguided X-ray and ultraviolet spectrograph.

THE SUN'S VIEW of Skylab was the smiling face of the ATM canister, surrounded by four solar-power wings. Above is the orbital workshop with patch-upon-patch of astronaut repairs and, extending to the left, the rectangular solar panel that provided the main electrical power. Features of the smiley face are the doors and other access ports to Skylab's solar telescopes.

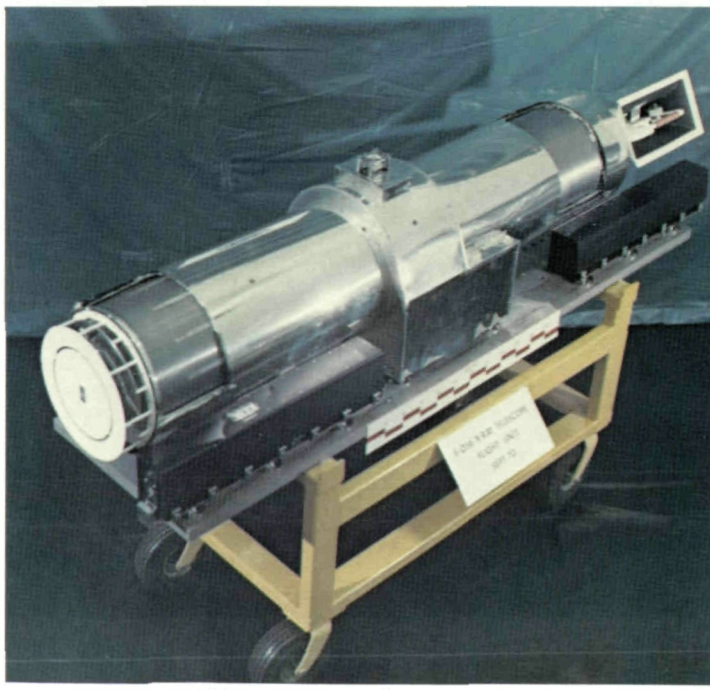


EIGHT SOLAR INSTRUMENTS without their protective coverings peer out of ATM's front end during final systems tests. Each instrument was attached to the supporting cross-like structure with legs designed so as not to introduce excessive structural loads or thermal gradients that could disturb the delicate alinement and pointing. During operation in space, the entire front of the package was covered with a shield containing aperture doors for each instrument to protect against solar radiation and contamination from surrounding space.

X-Ray Instruments

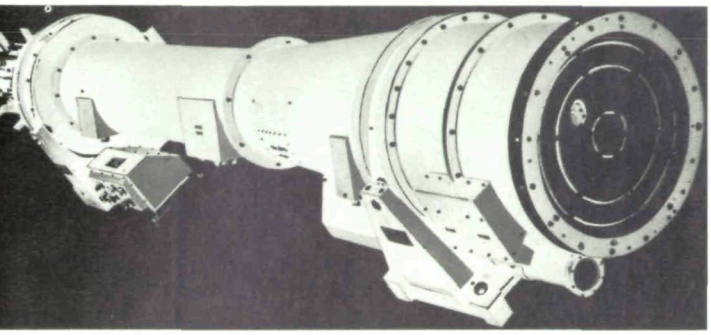
The two X-ray telescopes obtained data on the low and intermediate corona by photographing the full solar disk in broad wavelength bands through X-ray filters. Because conventional optics blocks transmission of X-rays, a special grazing mirror technique was used for collection and focusing of the incident energy. This technique also provided the maximum possible collection area within the telescope structure. In support of the two primary telescopes, auxiliary instruments provided a continuous record of the total X-ray flux in two bands, 2 to 8 and 8 to 20 Å. Also, a flare detector provided an X-ray image and automatic flare alarm to the astronauts at the control console as an aid in monitoring solar activity.

X-ray telescope (S-056).



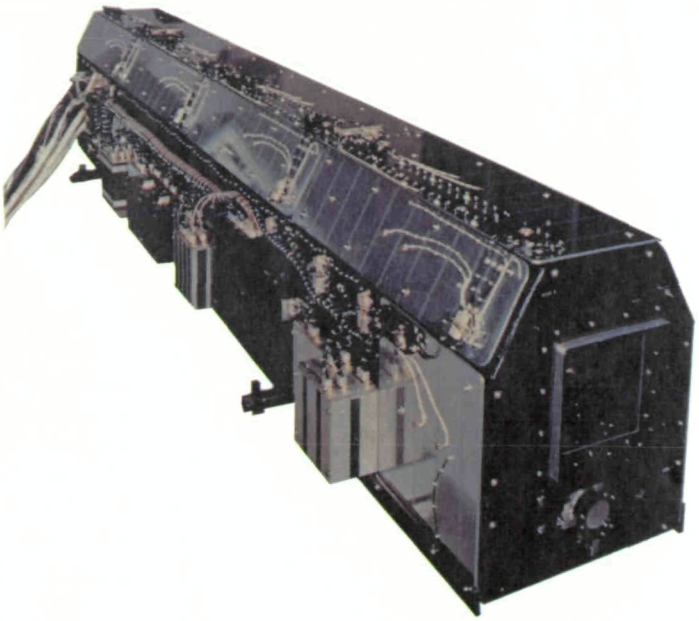
X-Ray Instruments

Instrument	*Sponsor*	*Wavelength covered, Å*	*Solar region observed*
X-ray telescope:			
S-054	American Science & Engineering, Cambridge, Mass.	2 to 60	Corona (1 to 1.5 solar radii)
S-056	Marshall Space Flight Center, Huntsville, Ala.	6 to 33	Low corona
	Aerospace Corp., El Segundo, Calif.		
X-ray and extreme ultraviolet camera (S-020)	U.S. Naval Research Laboratory, Washington, D.C.	10 to 200	Chromosphere, transition region, and low corona



X-ray telescope (S-054).

A hand-held X-ray and ultraviolet spectrograph was also carried on Skylab for photographing spectra of selected regions of the Sun by the astronauts during EVA.



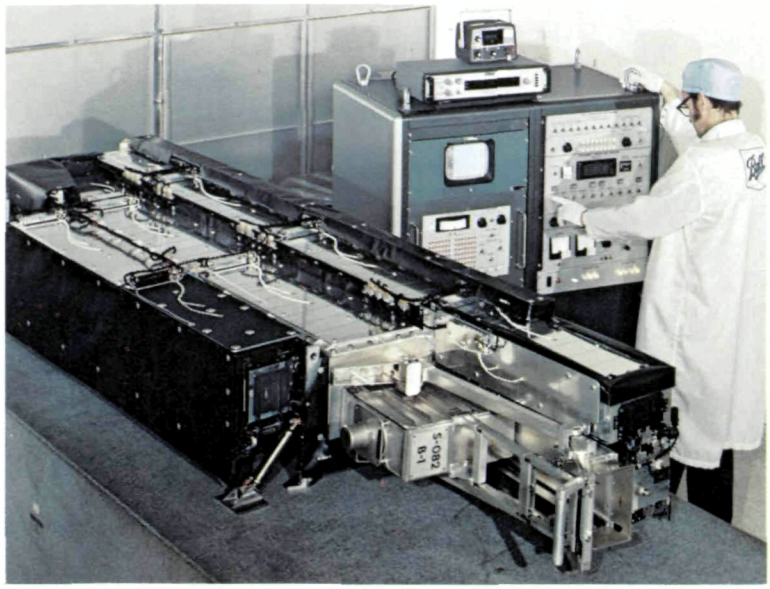
Ultraviolet spectroheliometer (S-055).

Ultraviolet Instruments

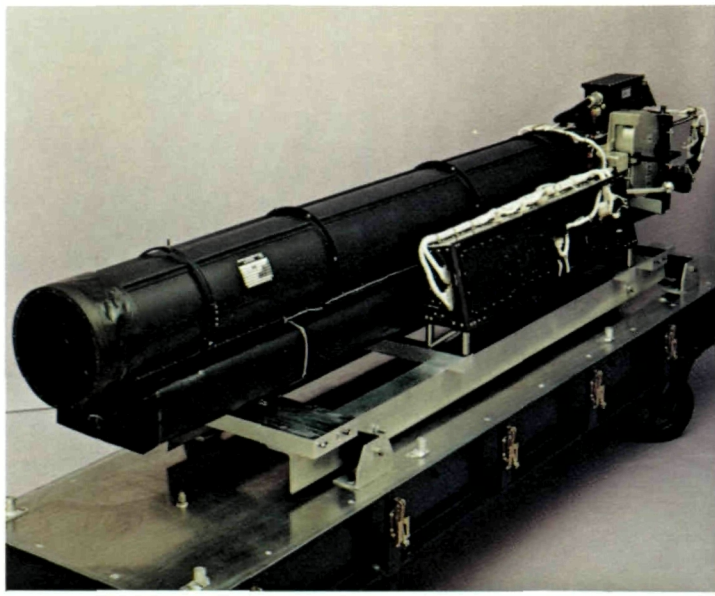
The three ultraviolet instruments on the ATM observed the chromosphere, the transition region, and the lower corona of the Sun. These instruments covered different wavelength regions and employed distinctly different data acquisition techniques. The spectroheliograph obtained photographs of the full solar disk as overlapping images, each in monochromatic light. The spectroheli-

Ultraviolet Instruments

Instrument	*Sponsor*	*Wavelength covered, Å*	*Solar region observed*
Extreme ultraviolet spectroheliograph (S-082A)	U.S. Naval Research Laboratory, Washington, D.C.	150 to 615	Chromosphere, transition region, and low corona
Ultraviolet spectroheliometer (S-055)	Harvard College Observatory, Cambridge, Mass.	300 to 1400	Chromosphere, transition region, and low corona
Ultraviolet spectrograph (S-082B)	U.S. Naval Research Laboratory, Washington, D.C.	970 to 3940	Chromosphere, transition region, and low corona



Ultraviolet spectrograph (S-082B).



White light coronagraph (S-052).

ometer performed digital scans of selected sections of the Sun in monochromatic light. This instrument recorded data in seven monochromatic regions centered on strong spectral lines and the continuum, simultaneously on magnetic tape. The data were later telemetered to the ground. The seven lines were chosen to sample distinct temperature regions (heights) in the solar atmosphere. The spectrograph photographed conventional spectra of selected regions or features of the Sun within a 2 by 60 arcsec field of view. The spectrograph was supplemented by an extreme ultraviolet monitor that provided video images of the full solar disk to the astronauts in a wavelength band of 170 to 550 Å. A second video camera provided white light (photosphere) images to the control console as an aid for instrument pointing.

The White Light Coronagraph

The white light coronagraph provided high-resolution photographs of the corona in the visible region of the electromagnetic spectrum. To block out direct sunlight and reduce diffracted light to an acceptable level, three external occulting disks were employed. This allowed observations of the outer corona from 1.5 solar radii to a distance of 6 solar radii from the center of the Sun. The optical elements of the instrument also performed the function of variable vignetting, which enhanced faint outer corona detail and suppressed blooming in the bright inner corona. A precise brightness calibration of the data was obtained by imaging direct sunlight through an 18 step wedge filter. A TV camera in the instrument provided real-time pictures of the occulted Sun to the astronauts at the control console.

The Hydrogen-Alpha Telescopes

Two H_α telescopes on the ATM were used for target identification, pointing, and reference. One was fitted with a 35-mm film camera to keep a continuous record of solar conditions and ATM

H_α *Telescopes and White Light Coronagraph*

Instrument	*Sponsor*	*Wavelength covered, Å*	*Solar region observed*
H_α no. 1	Harvard College Observatory, Cambridge, Mass.	6563	Chromosphere
H_α no. 2	Marshall Space Flight Center, Huntsville, Ala.	6563	Chromosphere
Coronagraph (S-052)	High Altitude Observatory, Boulder, Colo.	3500 to 7000	Outer corona

pointing during solar observing periods. Both telescopes gave the Skylab astronauts a real-time picture of the Sun in H_α through a closed-circuit television system displayed on a viewing screen in the Skylab space station. The telescopes were fitted with crosshairs, like a gunsight, for precise pointing of the ATM spar; each could expand or reduce the portion of the Sun seen in the telescope by means of a zoom lens. Each H_α telescope used a filter monochromator of the type described in chapter 2, which rejected all solar radiation except that in a narrow (0.7-Å) band centered on the H_α line. Four camera magazines holding 16 000 pictures each were exposed and returned to Earth from the ATM H_α camera; they provide a nearly continuous movie of the Sun for 9 months, to aid in analyzing the data from the principal ATM experiments.

OPERATION OF THE ATM

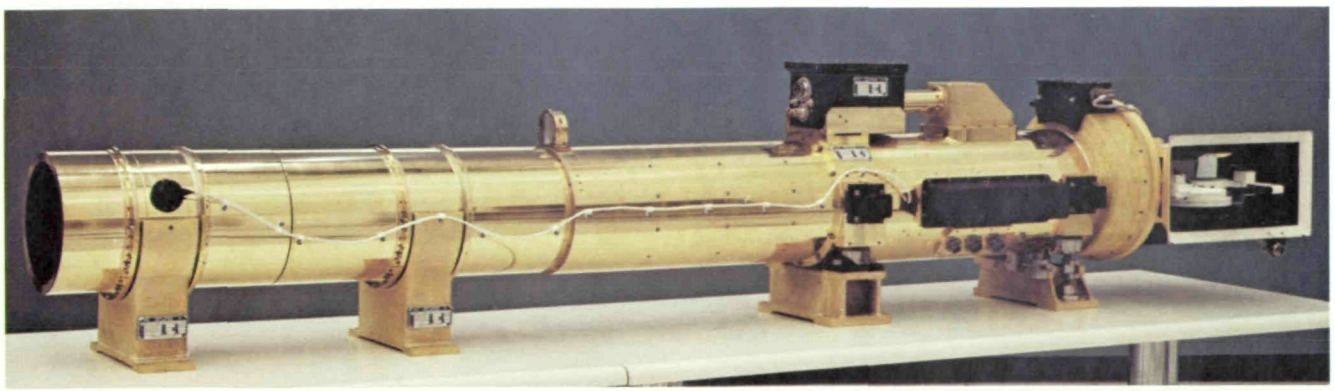
The clustered solar telescopes on the ATM provided an opportunity to perform simultaneous, coordinated observations of the Sun in many important wavelengths. They were like eight guns strapped together to fire at a common target. The instruments were carefully alined before flight and provided with in-flight methods of checking and correcting alinement changes. More important than the purely mechanical banding together of the eight telescopes, however, was the way they were scheduled and used to study specific solar problems.

In the years of preparation that preceded the Skylab launch, the various ATM investigators worked out joint observing programs for specific goals in understanding the Sun, projects that made optimum use of this unique assemblage of large solar telescopes above the atmosphere. In high-fidelity simulators at the Johnson Space Center near Houston, these observing schemes were tried, modified if necessary, and tried again. This resulted in tested observing programs that focused coordinated observations on every important feature of the solar atmosphere. Contingency plans were worked out and rehearsed for efficient, coordinated observations of the sudden and dynamic solar events anticipated during the Skylab mission: solar flares, prominence eruptions, and transient features in the corona. Plans were made for optimum observation of the total eclipses of the Sun that would occur during the operational lifetime of Skylab. When, a few months before the Skylab launch, the new comet Kohoutek was discovered on its way toward the Sun, plans and special efforts were developed by Skylab scientists for the most effective observations of that new celestial object.

Most difficult of all in the preflight scientific planning was the setting of priorities, the important choices between solar problems and, in some cases, between ATM instruments. The choices were crucial, for the solar scientists of Skylab were well aware that ATM's arsenal of coordinated instruments could not be duplicated again for many years. In planning programs and priorities, they sought the advice and invited the participation of solar physicists from all over the world to insure that the once-in-a-lifetime chance of ATM would be directed wisely at the most important solar problems.

Coordinating these preflight functions were teams of solar scientists responsible for each ATM

H_α no. 1 telescope.



SOLAR PHYSICIST Neil Sheeley monitors the operation of the Skylab solar telescopes from the control room at the NASA Johnson Space Center in Houston. In military fashion, crews of solar scientists and technicians kept watch around the clock in these control rooms during the 9 months of manned and unmanned Skylab operation.

experiment, the NASA mission planners, and the Skylab astronauts themselves. The final result of their joint labors was a set of carefully checked observational plans, in book form, with step-by-step instructions for integrated operation of the complex instruments. Copies were kept by each ATM experimenter and at control sites in Houston to be used when the mission began. Others were stowed in metal lockers on Skylab, long before launch, and fired into Earth orbit on May 14, 1973. When the first team of astronauts arrived, 11 days later, these copies of the observing plans were taken out and put to work. As the mission progressed, planning and training sessions continued on the ground, as new lessons were learned in space on the ATM. Observing plans and, in some cases, equipment itself was modified during the Skylab flight, and new goals were added as old ones were checked off. The second Skylab crew brought new ATM observing books in their command module. These books were, in a sense, "second editions" of the best book on solar observation that has ever been written. The third crew carried up even better third editions.

Throughout the 9-month Skylab mission, teams of scientists and engineers for each ATM experiment moved to Houston and worked at Flight Control Headquarters at the Johnson Space Center. In two special control rooms near the main mission operations control center, teams of solar physicists and engineers stood by around the clock to monitor the performance of each ATM instrument, to modify observational plans when necessary, and to advise the Skylab flight controllers on questions affecting the ATM instruments. During the two periods between manned operation of Skylab, these scientist teams continued their around-the-clock duty to operate those ATM instruments that could function in automatic modes.

Once each day throughout the Skylab mission, senior representatives of each ATM experiment in Houston would meet with other advisory personnel to plan a detailed solar observing schedule for Skylab for the following day, taking into account the current state of the Sun, predictions for its coming activity, preflight priorities of observing programs and goals, and any new opportunities or complexities that had arisen. In this they were supported by a continuous flow of timely information on the state of the Sun from ground-based observatories around the world. In return, these observatories were kept advised of Skylab's daily solar plans to allow coordinated ground and orbital observation of specific features and events. Of particular importance in this information network were the solar

PART OF THE PYRAMID of support for the astronauts in Skylab, these solar scientists in a Houston control room kept an up-to-the-minute account of all solar experiments and the state of the Sun itself, to insure that every minute of Skylab time was used to optimum advantage. In the background are individual consoles for each of the solar telescopes. A minute-by-minute observing plan was prepared each day in Houston in lengthy working sessions of solar astronomers, with input from solar observatories around the world. It was transmitted to Skylab by Teletype during the night and read by the astronauts the following morning. Unexpected solar activity resulted in a flurry of activity on the ground and rapid departures from the observing plan on Skylab.

forecast personnel of the National Oceanic and Atmospheric Administration (NOAA), whose around-the-world chain of solar observatories was dedicated to the support of the ATM effort. Nearly 300 solar scientists and nearly every major solar observatory in the world took part in one way or another in the Skylab ATM adventure, through direct participation or guest investigator programs, by ground support and solar patrol during the flight, or by using Skylab data after the mission.

From each daily planning session at Houston came a minute-by-minute solar observing plan for the ATM that was radioed to Skylab during the night and typed on the on-board teleprinter while the astronauts slept. When they awoke to start each new day, a printed daily solar observing schedule and forecast for solar activity was waiting for them, like the morning paper.

ROLE OF THE SKYLAB ASTRONAUTS

Most of the solar instruments on Skylab were descendants of instruments used in experiments flown on earlier, unmanned solar spacecraft. By and large, early designs called for automatic operation and control by radio command from the ground. The Skylab astronauts, in early concepts of the mission, were to aid the ATM solar program by retrieving and replacing camera magazines during EVA and by performing functions similar to those of observing assistants in ground-based observatories, such as aiding in pointing and target acquisition, checking instrument operation, and energizing and shutting down specific instruments.

This concept changed quickly as the complexities and potential of the ATM cluster of telescopes became apparent in preflight plans. Most obvious was the simple fact that the presence of an on-board observer and controller could add great flexibility and provide immediate response to opportunities, such as the sudden occurrence of flares and other dynamic solar events. This potential benefit was magnified by the fact that the Skylab astronauts were highly motivated and keenly interested in the Sun. Not just the scientist pilot, but all three crewmen of each Skylab mission were trained in operating the ATM, monitoring the solar disk for signs of activity, and activating the cameras to record solar events.

Thus, in the years preceding Skylab's launch, the astronaut crews and their backup teams were given full courses of study in solar physics, in programs arranged at the Johnson Space Center and at the major solar observatories in the United States. They became expert not only in the instruments on the ATM but also on the Sun and the solar problems that were to be examined. They knew the goals and limitations of each solar telescope, and the power of their coordinated use. They knew what to look for on the Sun and what it meant to find it. They knew the hard history of man's long efforts to get fleeting and distorted glimpses at what they would see with ease and clarity for hours and days on end.

As a result, the Skylab astronauts served solar physics far beyond what was originally asked of them. Through enthusiasm alone they added many hours and many new opportunities to the planned observing goals. They worked with the scientists on the ground, via radio exchange, in planning new programs and modifying others. They kept watch for flares and devised their own new ways of predicting flare occurrence. Their responses were fast and unerring. They enjoyed their solar tasks and the challenges they presented. On occasion, during the long night watch at Houston when the astronauts were presumed to be asleep, ATM ground controllers would see their control panels light up, indicating that far above, telescope doors had been quietly opened and a spectrograph or coronagraph had been turned toward the Sun by a dedicated astronaut anxious to add a few more hours and a few more photographs during man's best chance to seek the secrets of the Sun.

The most impressive contributions of the astronaut crews became apparent only after Skylab was launched, when on repeated occasions they turned disaster to success by in-flight repairs and modifications. Their first spectacular role in patching the Skylab together after a nearly catastrophic launch mishap is well known. Less heralded, but equally important to the ATM solar program, was a sequence of efforts that salvaged ailing solar experiments again and again and kept them running at full speed until the planned end of the mission. These repairs were chiefly done during extravehicular activity. They included pinning open experiment doors that had failed in closed position, replacing a jammed camera, twice removing thread-like objects that collected on the coronagraph occulting disk, and repairing a shutter mechanism and jammed filter wheel with a screwdriver. Inside

Skylab, at the ATM console, a defective television tube was replaced in orbit and a number of modifications were made to various control functions, following specific failures or recommended improvements. One of the large ATM instrument cameras was disassembled and reloaded with fresh film during orbit, adding significantly to the total amount of data acquired.

CONTROL OF THE ATM TELESCOPES

Solar observations on Skylab were controlled from within the multiple docking adapter—a cylindrical room about 3 m in diameter that was the docking port for the command module and the connecting link between the ATM and the orbital workshop, in which the astronauts lived.

The multiple docking adapter was the common laboratory for much of the science that was performed on Skylab. It was a laboratory with neither floor nor chairs, because none was needed in the weightless, zero-gravity conditions in Skylab's orbit. Bolted to the walls were film vaults and storage lockers, apparatus for metal processing experiments, controls for the down-looking Earth resources cameras, and the great Wurlitzer-like console from which the ATM solar telescopes were directed and monitored.

WITHOUT THE BURDEN OF GRAVITY Astronaut Owen Garriott sits at Skylab's ATM control console with no need of a chair. Before him is the complex array of controls for Skylab's solar telescopes. His feet, in special shoes, are anchored to a plate below, to keep him from floating away from his work.

On the front of the ATM console were the many switches and indicators that were used to control electrical power to each telescope, to open and close experiment doors, and to change the operational pace of each instrument, which was rapid and intense at times when the Sun was active or explosive but was slower during routine patrol and quiet-Sun experiments. Dials and counters displayed instrument readiness conditions and, as on any camera, showed how many frames remained in each film magazine. Other displays and controls were used to correct instrument alinement and to check the important cross-alinement between different ATM telescopes.

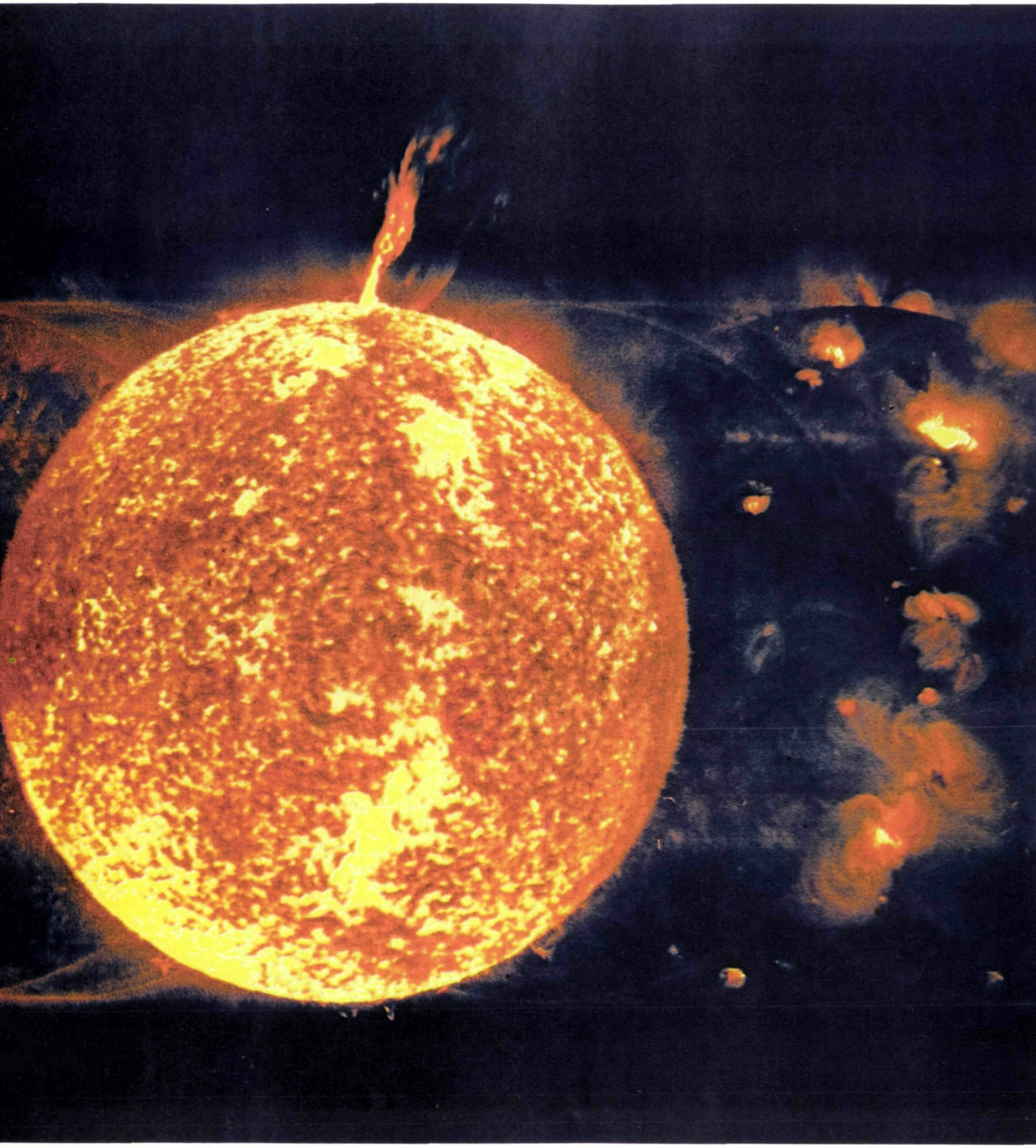
Two television screens on the ATM console showed the astronaut operator what the solar telescopes saw, as through the viewfinder on a single-lens reflex camera. He could direct the massive telescopes with great precision by watching the crosshairs on the video screen and moving the ATM cluster by means of a small control lever at his fingertips on the console.

The video cameras and TV screens offered a unique, real-time look at different layers of the solar atmosphere: photosphere, low chromosphere, high chromosphere, transition region, or corona. Beside each video screen was a selector switch that offered five different channels of solar viewing available in any combination:

Channel	*View*
1	A full view of the disk of the Sun in white light, showing the location of sunspots
2, 3	Either of two views of the chromosphere in H_α light, through zoom cameras on the two H_α telescopes—with a power zoom switch the astronaut could bring either H_α picture to higher or lower magnification for close examination or a survey of the entire disk
4	An unprecedented view of the transition region and low corona over the entire disk of the Sun, as seen in the extreme ultraviolet through the extreme ultraviolet monitor on the ATM ultraviolet spectrograph
5	A view of the outer corona as seen by the white light coronagraph

Live video pictures of the Sun in white light or H_α are commonly used in modern solar observatories for monitoring solar activity. But when the Skylab astronauts first switched to channels 4 or 5, they saw the Sun as no one had ever seen it before. In switching from channel to channel and looking at all the important layers of the Sun in real time, they enjoyed an overall view of the Sun that until that time had been denied the eyes of man. Nor had any astronomer ever had before him the fingertip controls of so many different astronomical instruments as were on the ATM control console.

With these new tools, and aided by the long preparation and worldwide support that backed the ATM, success was achieved that exceeded all expectations. The ripples from that achievement go far beyond solar physics and astronomy, through all of science. Perhaps the greatest mark left by Skylab was the demonstration, through the ATM, of the staggering power of a coordinated and regimented approach to the solution of specific problems in science.



5

The Solar Results From Skylab: An Introduction

What is the Sun? If the science of astronomy could solve this great problem, it would be nearly capable of solving that of the entire Universe.

—Amedee Guillemin, 1870

Since February 1974 when the final Skylab crew splashed down in Pacific waters, thorough analysis of film and other solar data from the three Skylab missions has produced many significant advances in our understanding of the Sun. Hundreds of articles have already appeared in scientific journals and will become the basis of a modern reappraisal of our nearest and most important star. Many more will follow. This first phase of interpretation has involved not only the corps of solar scientists that took part in the operational phases of the Skylab program, but nearly all the solar observatories on Earth, and many of the world's solar astronomers. Because changes on the Sun are felt on Earth as well, the new solar results have affected areas of Earth science as well as the basic study of other stars.

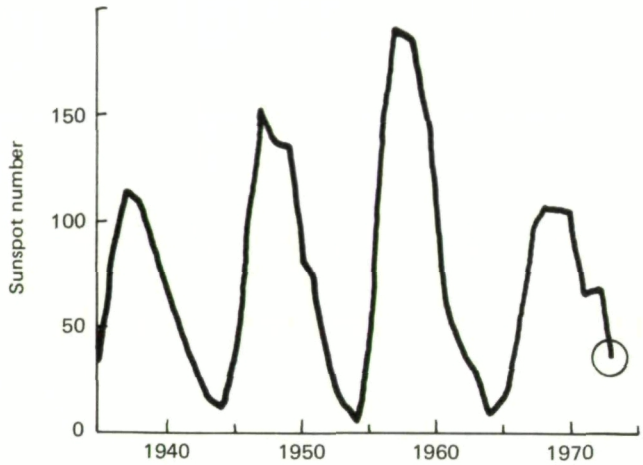
Among the important results from Skylab's telescopes are new insights into the basic processes of solar behavior, into interplanetary and terrestrial studies, and into the theoretical understanding of magnetic plasmas and atomic spectra. Other important results are told more easily in pictorial form. The remainder of this book displays a number of such pictures. These illustrated results of Skylab are divided into two chapters. Chapter 6 tells Skylab's findings of the quiet, or inactive Sun, and chapter 7 of its more violent and active features. In each chapter the results are divided into several subject areas, selected from the areas of solar physics in which Skylab made significant advances.

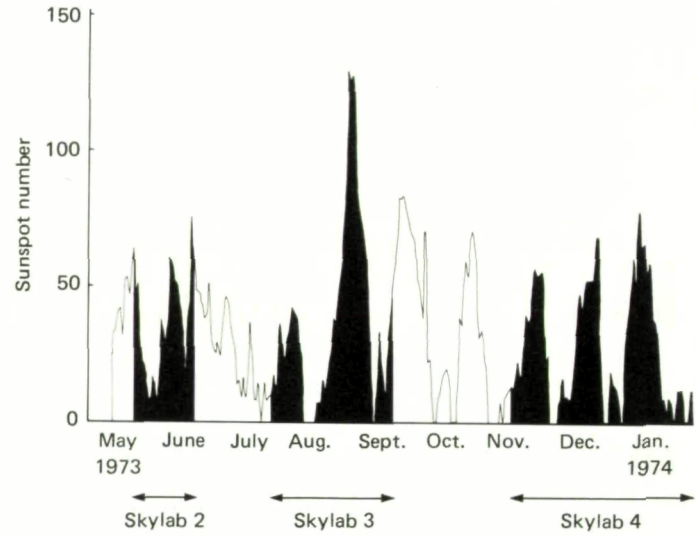
The division into quiet and active solar behavior recognizes the fact—known long before Skylab—that the atmosphere of the Sun is ever changing. In the long term, of years and decades, solar behavior follows a cycle of about 11 years, with the last maximum in 1968 and 1969, as shown in the graph of annual averaged sunspot number at center left on the next page. During the 9 months of Skylab's intensive observation of the Sun—an inset circle on the same graph—solar activity was in the long term falling, to a minimum that was reached in 1976-77. The Sun, in the words of solar astronomers, was getting more and more "quiet."

Such descriptions apply only on the average, and although 1973 and 1974 were years of declining action on the Sun, there were days and weeks when the Sun was far from quiet. A daily measure of solar activity during the 251 days of active Skylab operation is shown at center right on the next page. High values indicate days when there were many sunspots and other signs of solar activity; when the plotted values are low, the Sun was quiet. The three periods when Skylab was manned by astronaut crews are black.

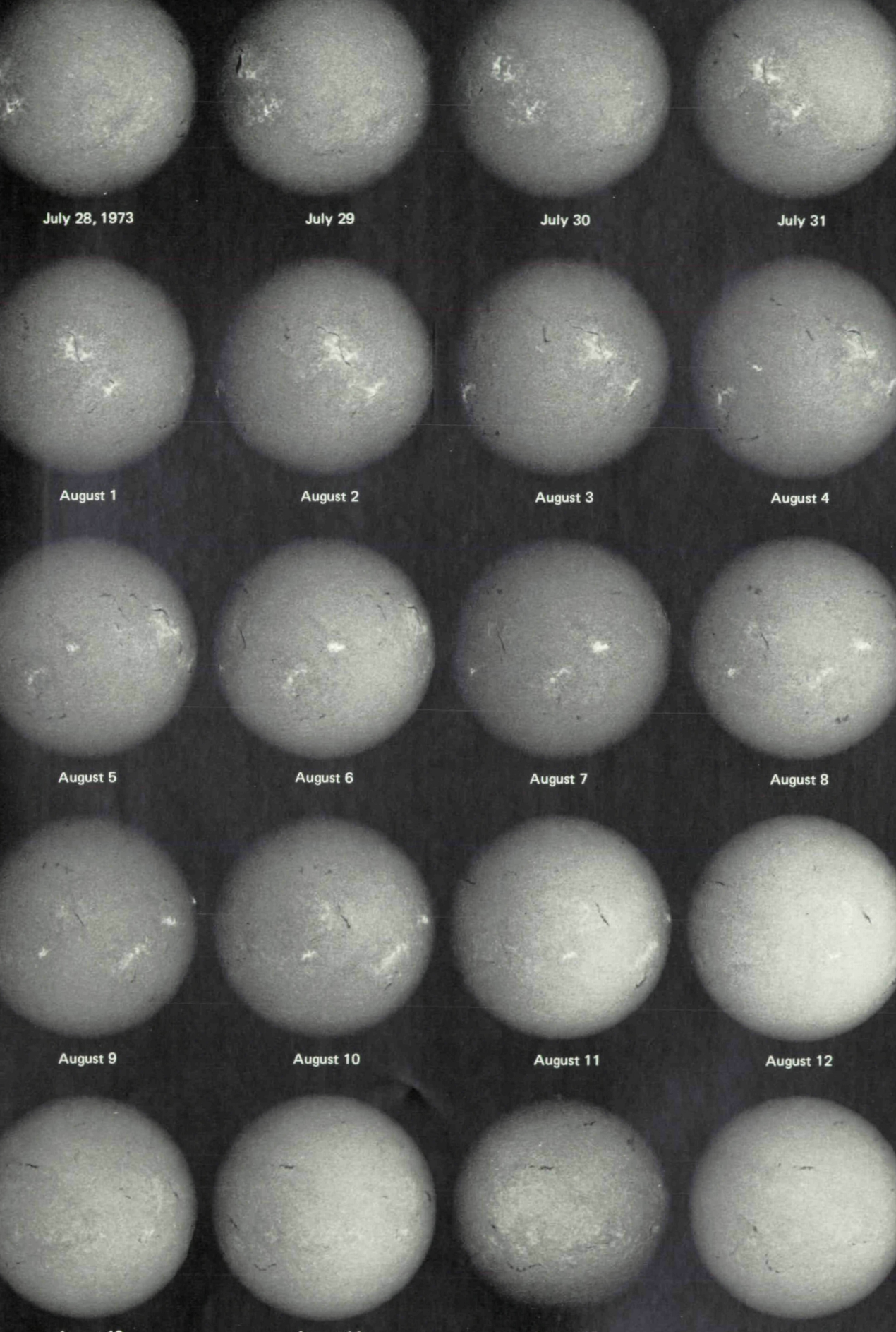
Solar scientists had hoped to observe both active

and quiet periods during Skylab, to sample the full range of solar behavior. As we can see, the Sun cooperated fully. When astronauts Conrad, Kerwin, and Weitz first docked with Skylab, on May 25, the Sun was active; solar behavior then calmed during the middle of their 28-day mission and rose again toward its end. During the second manned mission, after an initial burst of solar activity, astronauts Bean, Garriott, and Lousma saw the spectacle of an absolutely quiet solar face for several days. There were no sunspots. Then, in early September, the Sun surged to levels of activity more like the years of maximum in the solar cycle. A daily diary of the Sun showing the changing solar activity during their 59-day mission is shown on the following pages. During the long third mission, Astronauts Carr, Gibson, and Pogue watched the Sun alternate between equal intervals of action and quiet—the solar surface divided down the middle in two halves of opposite character. With them, when they returned to the surface of Earth at Skylab's end, were rolls of film that told of both quiet and active Suns.





CHANGING FACES OF THE SUN, one for each of the 59 days spent in orbit by Skylab's second crew, are shown as a solar diary in the next three pages. Two pages would have sufficed for the 28 day record of the first crew; the third crew, in orbit for 84 days, would have needed six. During the 59 days shown here, the Sun spun more than two full turns around its axis. Solar rotation is apparent in these daily portraits, as are real changes on the Sun. Each photo shows the lower chromosphere in the red (H_α) line of hydrogen; bright features are centers of activity on the Sun. Skylab's astronauts watched these constant changes in similar H_α pictures on live television at their solar telescope control console.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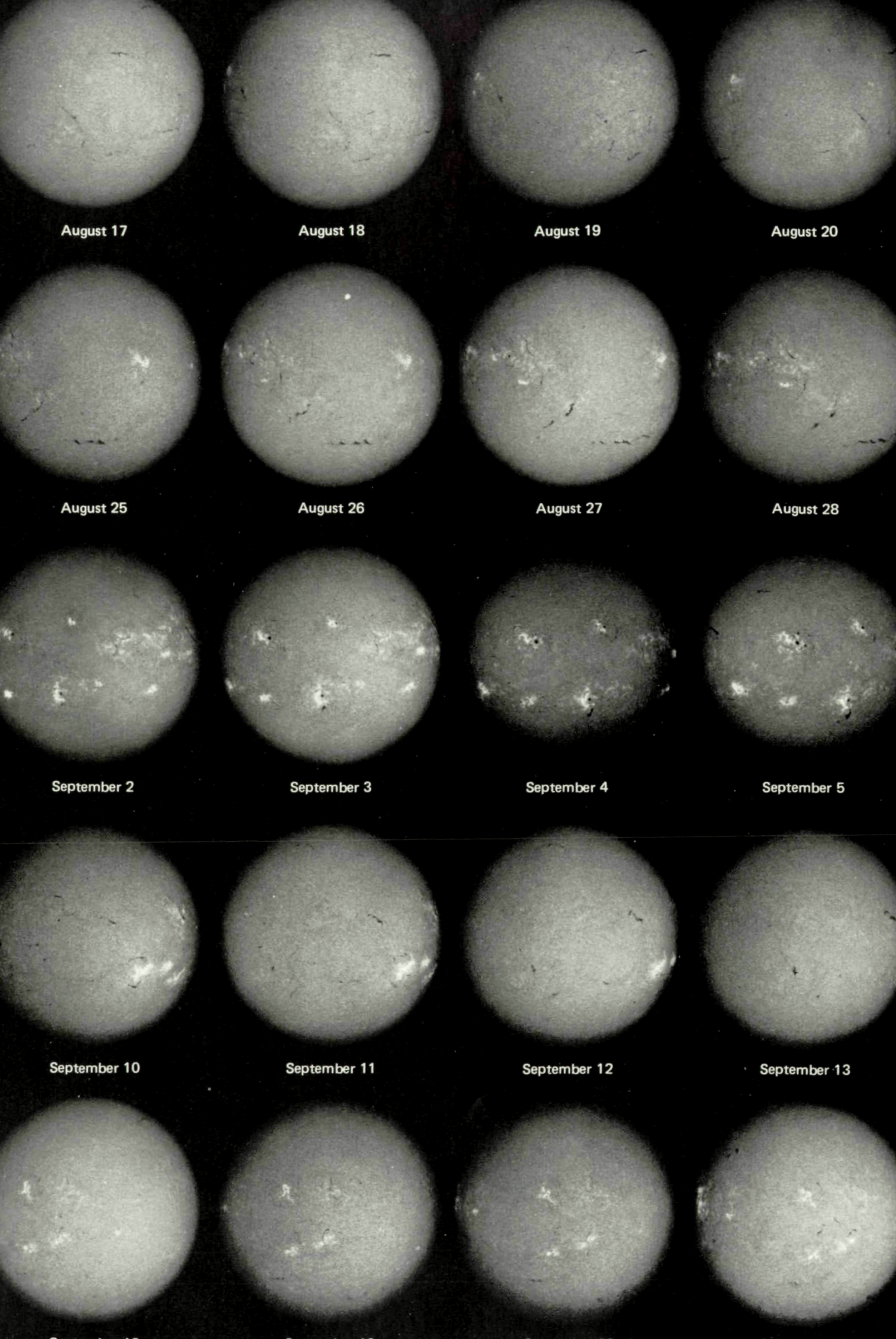
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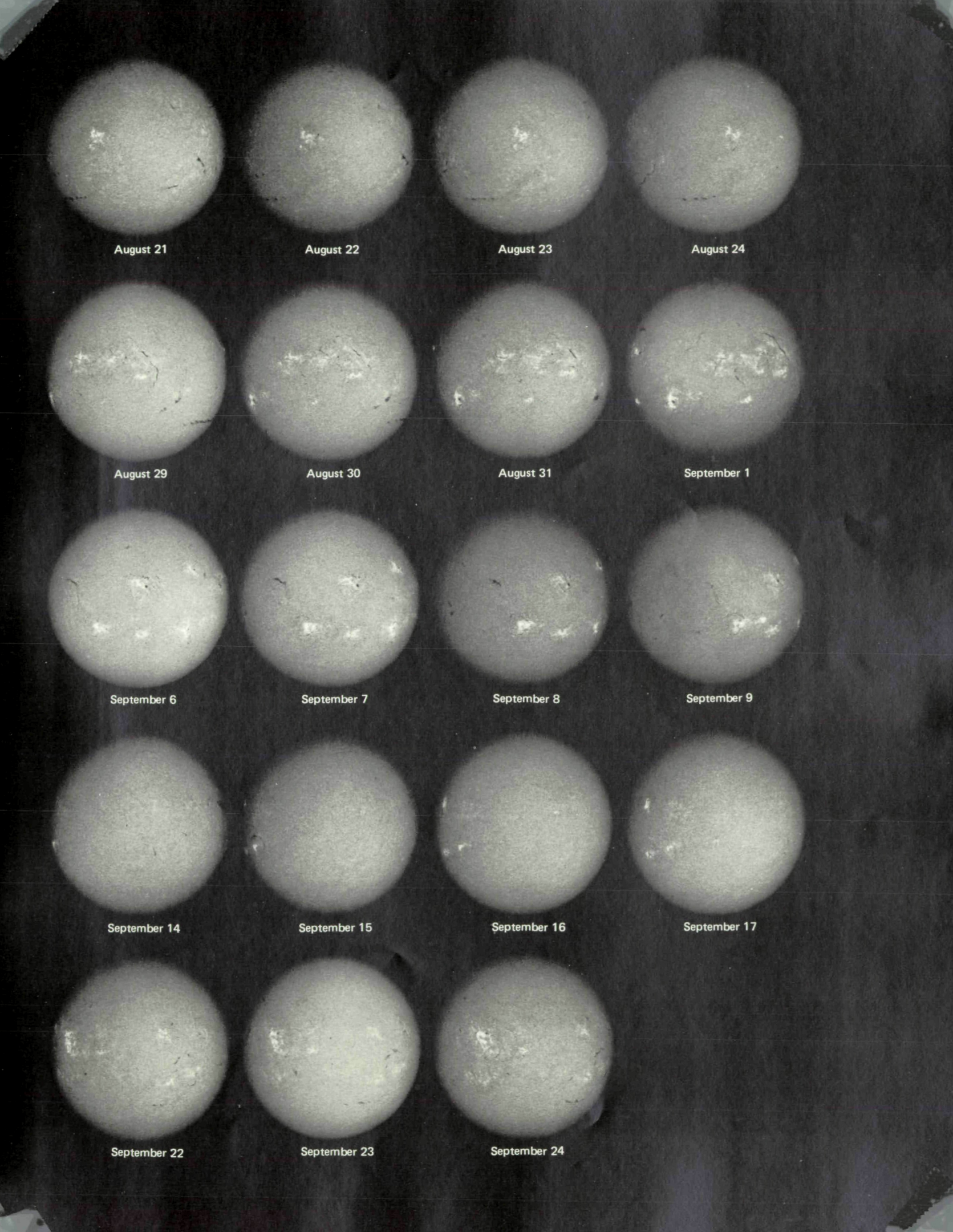
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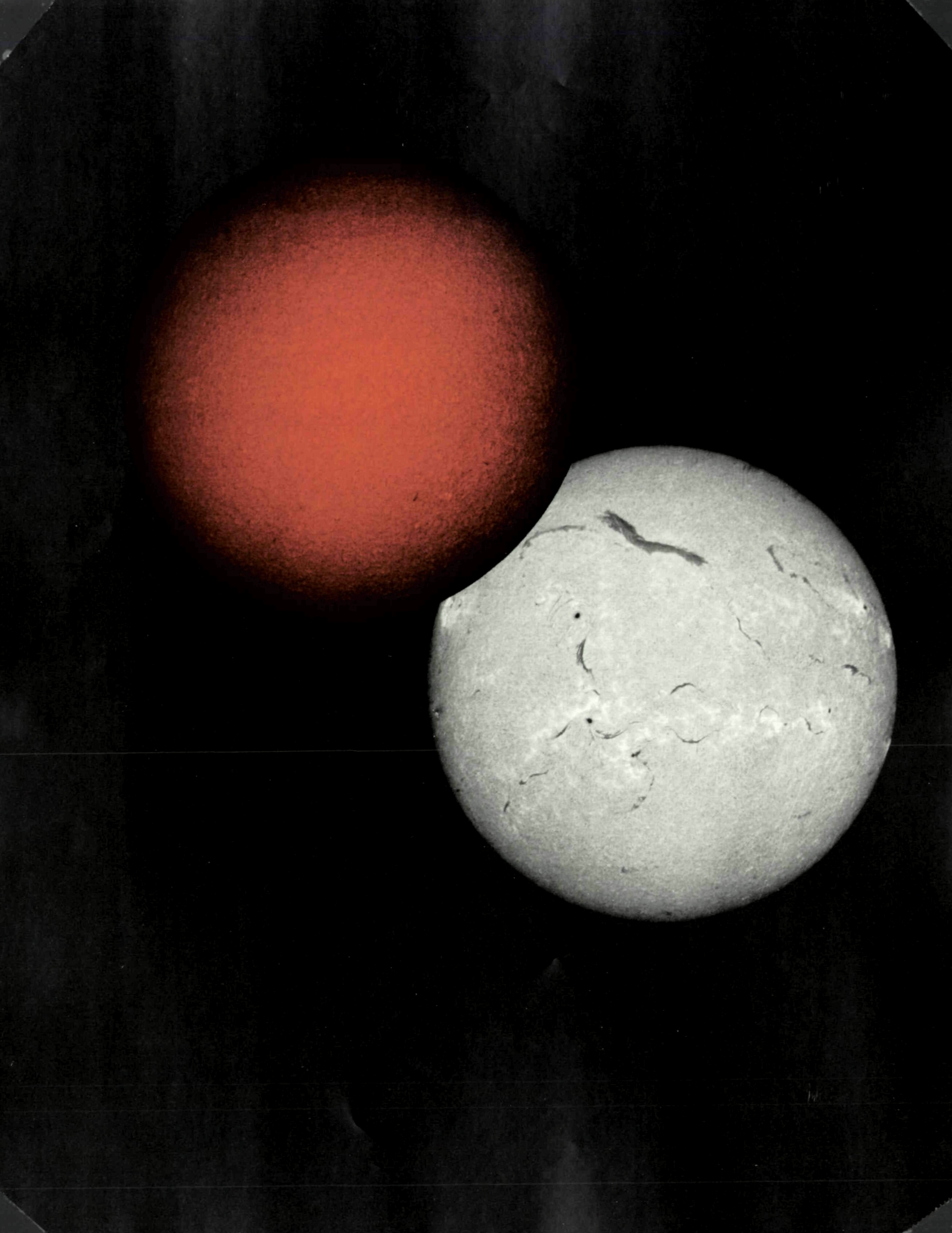

6
The Quiet Sun

Oh, one other comment that should be of interest. . . . We did get a couple of glimpses of the corona also at the end of the orbit. It's the first time that we've seen it since yesterday. And there are definite changes in the southwest quadrant—a whole array of streamers—that were not there last night.

—Astronaut Owen Garriott, Sept. 7, 1973, 13:21

The raging furnace of the Sun is never quiet and its surface never still. There is always change and, when one looks closely enough, dynamic action in the various features that make up its many faces. The Sun described as "quiet" still has a boiling surface of bubbling granules, a network of heaving supergranules, and sunspots that come and go. Spicules roughen the edge of the quiet chromosphere, shooting upward in pointed waves that rise as high as 20 000 km into the corona. Magnetic fields change and shift their shapes with effects felt throughout the solar atmosphere. Long-lived, quiescent prominences decorate the quiet Sun as does a distended and ever-changing corona. On the Sun, as on Earth, "quiet" is a relative word.

Skylab scientists were as interested in the quiet Sun as they were in the really dynamic action on its surface, for the fundamental processes of the star can be seen best, and sometimes only, on its relatively undisturbed surface. These quiet-Sun observations lead to an understanding and important models of the basic structure of the solar atmosphere including its temperature, density, chemical composition, magnetic fields, and the physical mechanisms that create and hold the chromosphere and corona to the Sun. Truly eruptive features of the Sun, like flares, sprays, and active prominences, can only be understood against a basic understanding of the undisturbed background Sun.

Skylab observations of the quiet Sun gave astronomers their first clear looks at the real extent and complexity of the entire solar atmosphere; revealed the changing vertical structure of previously known features such as sunspots and the chromospheric network; and identified, for the first time, the varied magnetic loops that make up the corona. From Skylab have come the first clear pictures of the changes that consistently alter the form of the outer corona as it adjusts to surface disturbances and to changing magnetic fields. The details and changing nature of the transition region—the shallow but important layer that separates the cooler chromosphere and hotter corona of the Sun—were for the first time seen. Also, the nature and importance of holes in the corona that stand out as dark, extended open regions in X-ray and ultraviolet pictures were established. From coronal holes the solar wind pours outward from the Sun apparently unabated. Skylab's continuous observations of coronal holes, coupled with measurements at Earth of the solar wind and geomagnetic wind, clearly established that coronal holes were the long-sought source of recurrent solar wind disturbances that buffet the upper atmosphere of Earth, making possible dramatic improvement in the prediction of the effects of the Sun on Earth.

Six aspects of quiet-Sun behavior or appearance in which Skylab observations made important advances are discussed in this chapter: general findings from the appearance of the Sun in the ultraviolet, the poles of the Sun, its appearance in X-ray wavelengths, coronal holes, quiescent prominences, and the outer corona. In each category are shown a number of selected findings that are grouped in double-page sections. Information on each picture may be found in the photo credits section.

IN THE ULTRAVIOLET: THE INVISIBLE SUN

The great power of Skylab's solar telescopes enabled man to see the Sun in light that from the surface of Earth is never seen: the invisible spectrum in ultraviolet and X-ray wavelengths that is totally absorbed by the dense atmosphere of Earth. Solar astronomers knew that in hidden ultraviolet wavelengths that originate in the upper chromosphere and transition region lay the secrets of these important layers of the Sun: their chemical composition, temperatures and densities, and physical processes—how they changed and how they were related to the vastly different corona above and photosphere below. There was no doubt that in the ultraviolet lay the secrets of the changing Sun, and key pieces long missing from the puzzle of the solar atmosphere. Rockets and orbiting solar observatories had begun the exploration of the ultraviolet Sun, but it was left to Skylab with its versatile, observatory-sized telescopes of unequaled spatial resolution and staying time to observe the invisible, ultraviolet Sun in the same intensive way that for centuries man had seen the visible light Sun.

From analysis of the thousands of Skylab ultraviolet pictures and spectra has come indeed a detailed understanding of a new Sun: a full picture of spicules and the chromospheric network; the discovery of a class of new features found only at the solar poles; new insights into the ways that wave energy is transmitted upward to heat the outer layer of the Sun; the first detailed pictures of the transition region; a total picture of the real extent of prominences, sunspots, coronal holes; and the key role of the snarled and twisted magnetic forces that tie together so much of what we see on the Sun. From ultraviolet spectra taken by Skylab has already come the identifications of 65 new emission lines originating in the transition region and corona—more than twice the number identified in the preceding 25 years of rocket exploration, allowing a more complete description of the physical conditions and processes that hold the secrets of the Sun.

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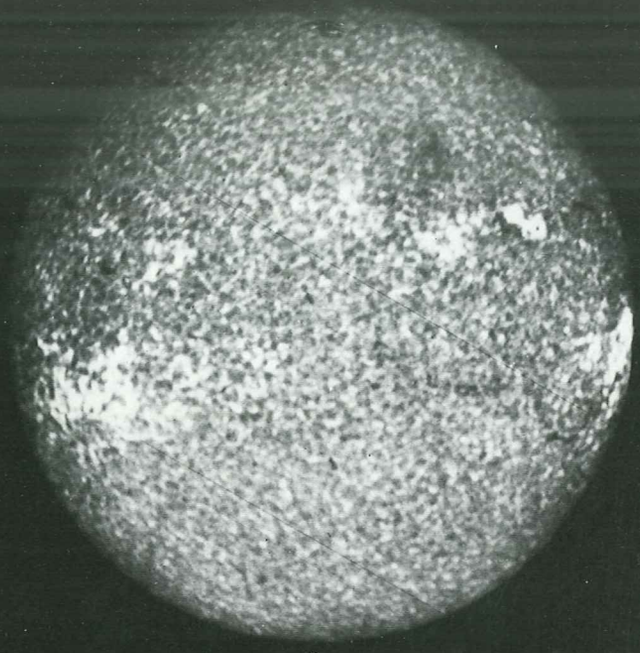

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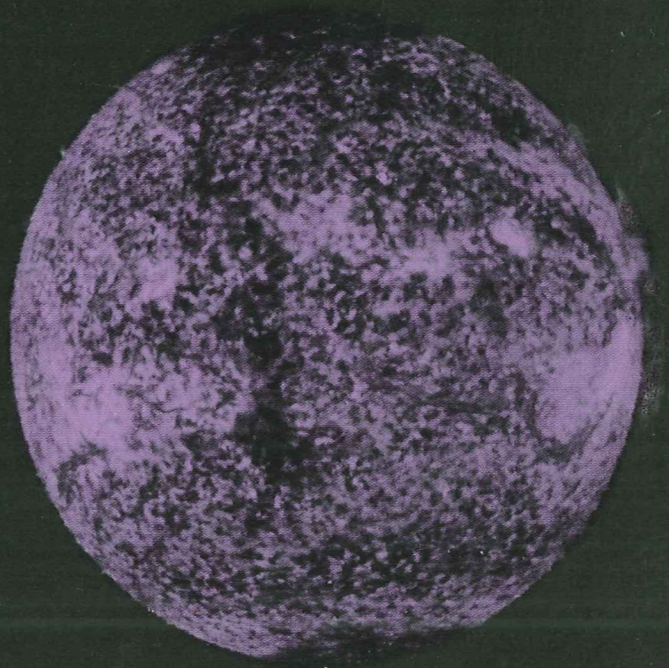

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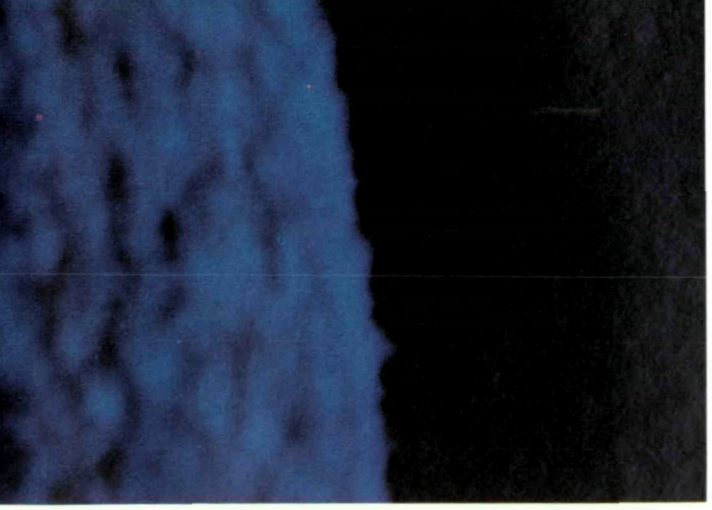
A SKYLAB VIEW of the ultraviolet Sun (4) rounds out the modern picture of our nearest star. Ultraviolet light from the Sun cannot penetrate Earth's atmosphere, yet it carries information on the Sun's most active and interesting layers—hotter and higher than the levels seen in solar views made from the ground (1, 2, 3). A magnetic map of the Sun (1) locates strong magnetic fields in the photosphere—as white areas for one magnetic polarity and black for the other. In H_α light (2) we see the low chromosphere, and in (3) a chromospheric layer slightly above it. Dramatic new features appear in the ultraviolet view (4). Dark regions at both poles of the Sun and extending across the equator disclose the existence of holes in the corona. Strong magnetic areas, or active regions, which appear bright in H_α (2) and calcium (3) are fluffier and more arched in the ultraviolet, where in higher layers we begin to see loops that lace these regions together. The remainder of the ultraviolet surface is covered by a mottled network, also seen in (3), which traces the all-over pattern of circulation cells in the solar atmosphere. At the edge of the ultraviolet Sun a band of large prominences appears like a towering line of cloudbanks tens of thousands of kilometers above the solar surface.



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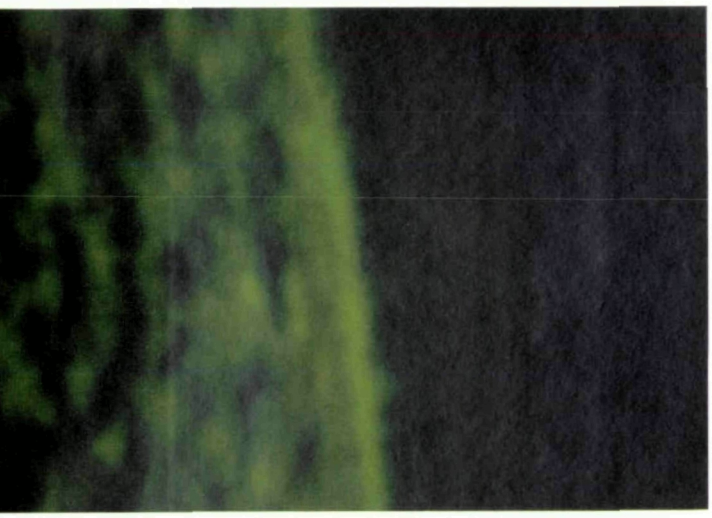

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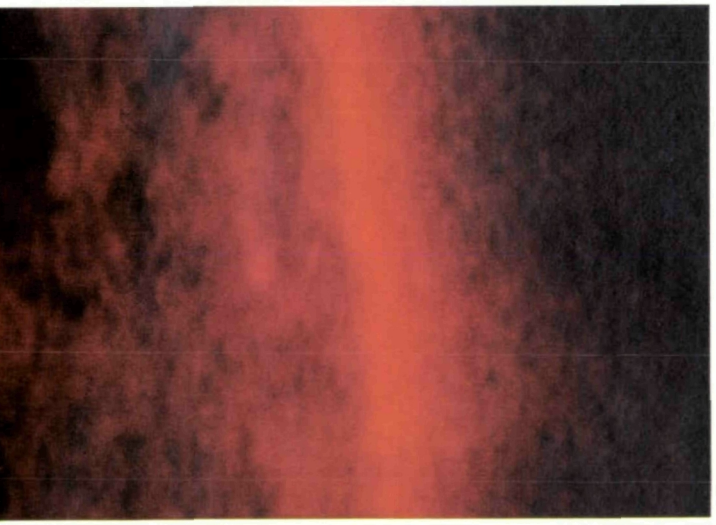

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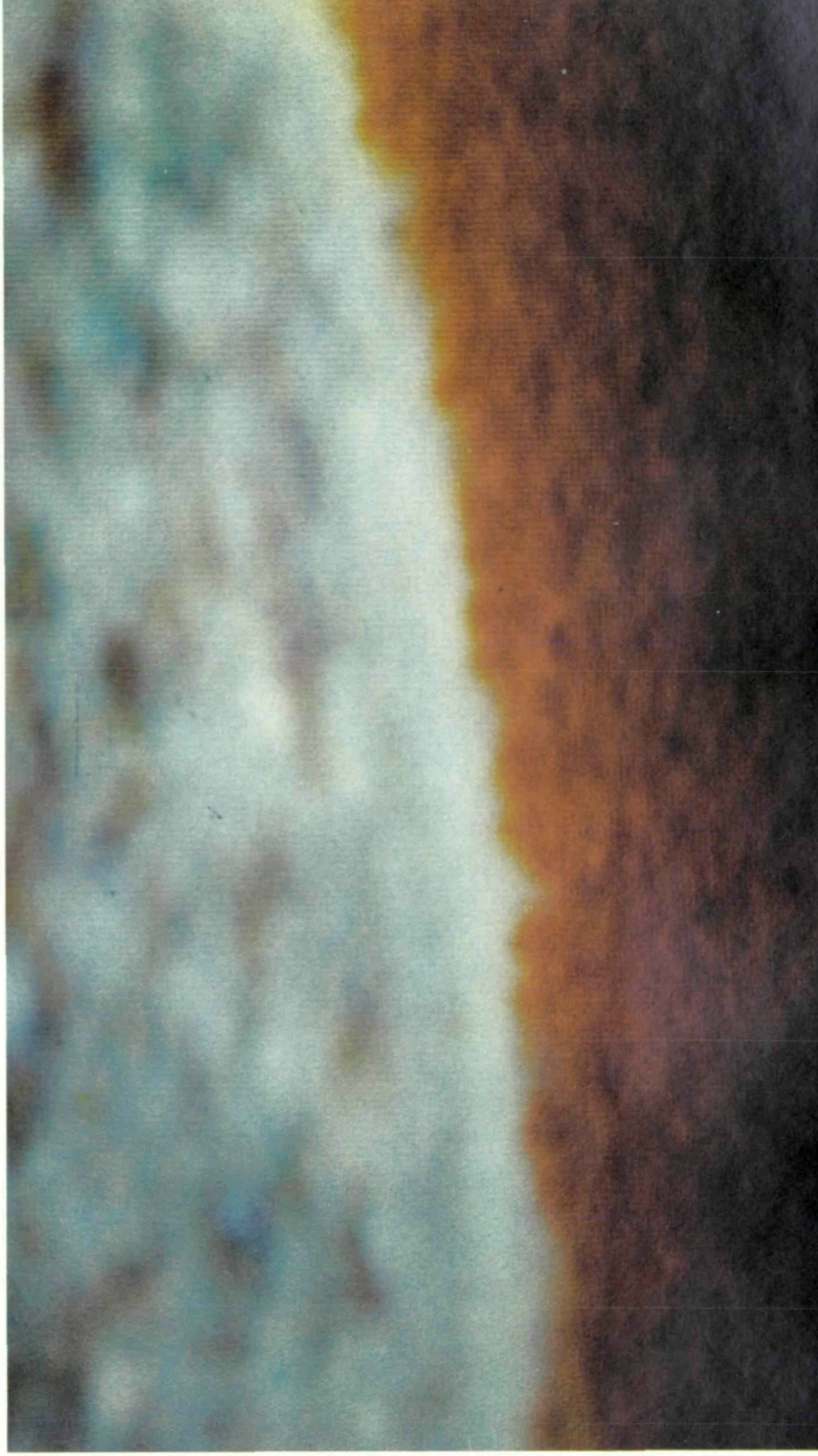
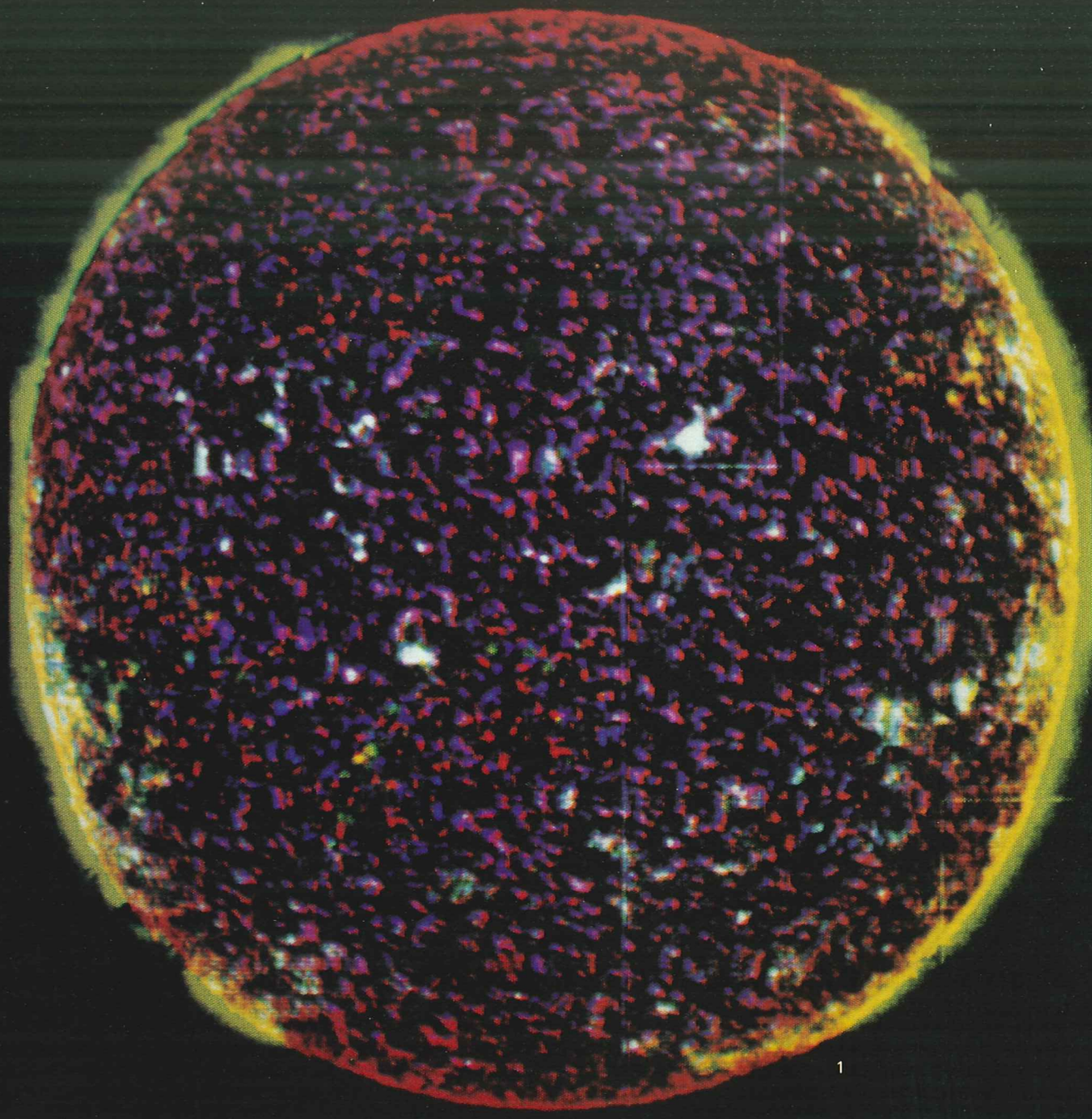
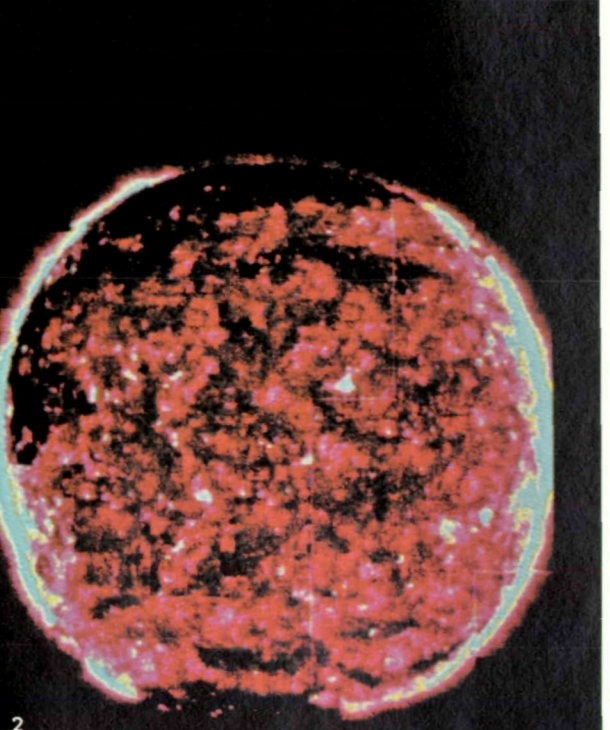


ATMOSPHERIC LAYERS on the solar horizon are peeled apart in pictures made in discrete ultraviolet wavelengths (5-7), then reassembled in the larger view (8). Colors were added in data reduction to distinguish different layers. Comparisons of features in separate and combined pictures demonstrate connections and relationships otherwise unseen. The high chromosphere (5) at about 70 000 K, colored blue, is marked by sharp spicules at the limb and a pronounced network of convective cells over the entire surface. In green (6) we see the elusive transition region that separates chromosphere and corona, sampled at a temperature of about 300 000 K. The bright ring that surrounds the edge of the Sun is an edge-on view of this distinctive layer, which then diffuses upward into the even hotter corona. At a wavelength that samples coronal temperatures (7), we see a vastly different view—the hot, inner corona, stretching higher above the solar limb, thin and diffuse, like the rosy glow of coming dawn. At this height the network of convective cells has disappeared and in its place clumps of bright emission outline parts of magnetic loops. Blue, green, and red pictures were added together in (8). Where features of the separate layers overlap, they combine to produce white, as at the network boundaries. Features distinctive to one layer, like the tenuous corona, show up in their respective colors.



QUILTED TOGETHER TO PORTRAY A QUIET SUN (1) are 44 square picture segments made in ultraviolet wavelengths 11 days before the final Skylab crew shut down the solar observatory for the last time. The collection of square scans, carefully recorded to insure a proper fit, kept Astronaut Gibson busy for 3½ hours, while Skylab circled Earth six times. Each square was simultaneously scanned in seven wavelengths, sampling seven different temperature layers of the solar atmosphere. Three (2, 3, 4) are shown on the opposite page, color-contoured to emphasize differences in brightness. The middle chromosphere (2), at a temperature of about 20 000 K, shows hotter, brighter regions as white splotches; cooler, darker ones are black. The convective cell pattern of the chromospheric network covers the Sun, fading near the poles. A higher, hotter layer of the chromosphere (3) presents a different view. The white, bright ring around the Sun is spicules seen edge-on, signaling the start of the transition region. The ultraviolet corona (4)—a still higher, hotter layer—looks almost unrelated to the layers below it. The network of convective cells has disappeared; structures are now clumpy, larger, and shaped by other magnetic fields. The anomalous polar regions, hinted at in the chromosphere (2), are now revealed as holes in the corona. Bright points appear like glittering flashes of light. The composite view (1) combines the three wavelengths with new colors: blue for (2), red for (3), and green for (4). Where bright areas coincide, their colors add to produce white, as in the bright dots that are concentrated in middle latitudes on the Sun, where sunspots and other activities are born. The greenish ring around the Sun identifies the low corona, which is absent at the polar caps where chromospheric red shows through.



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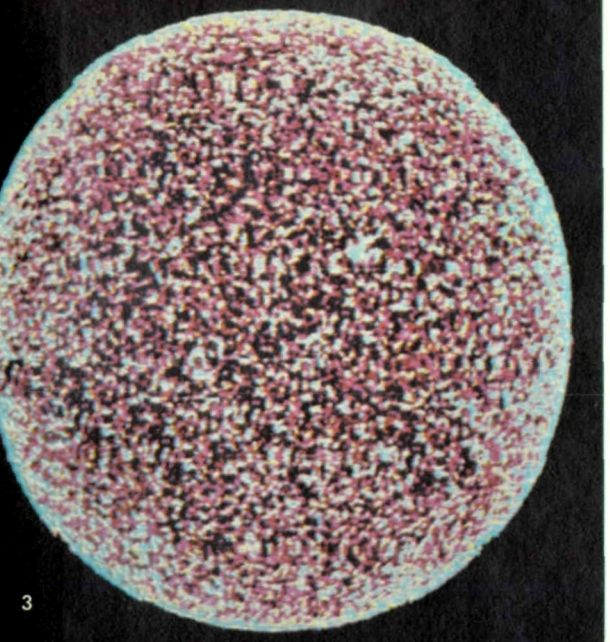

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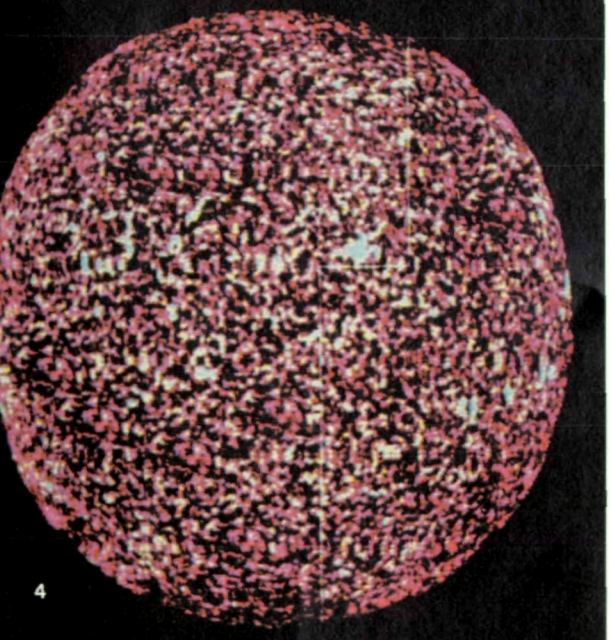

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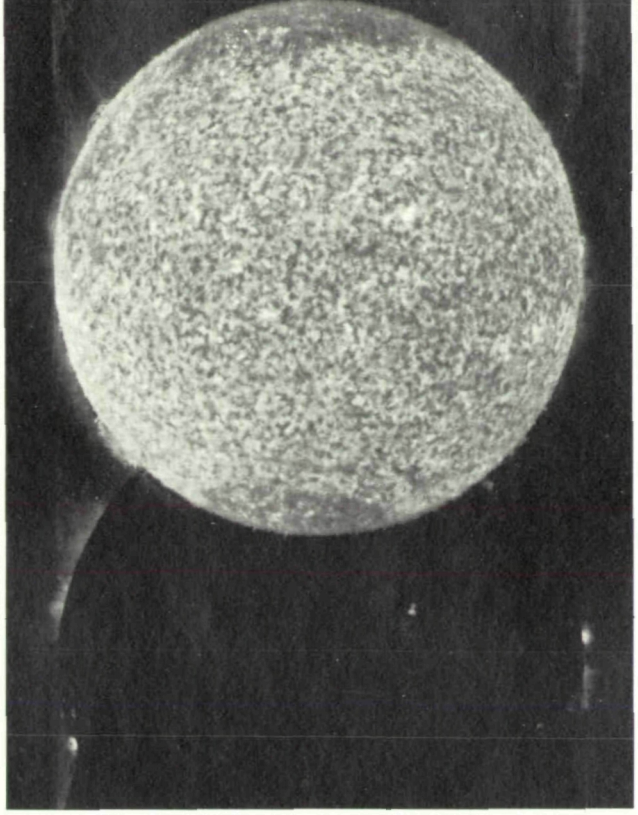

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ANOTHER SKYLAB TELESCOPE made instantaneous photographs of the full solar disk in many ultraviolet wavelengths, as overlapping images of the Sun. In (5) we see two simultaneous pictures of the quiet Sun made on the same day that (1-4) were made; (6) compares the same pair for a more active Sun. The bright solar image in each pair is the chromosphere at temperatures of 30 000 to 90 000 K. Below it, slightly overlapped, is a simultaneous image of the 2.5×10^6 K corona. The quiet corona (5) is almost blank, except for the glow of distant features on the opposite side of the Sun. Chromosphere and corona are vastly different in (6): Bright, active regions in the chromosphere appear without exception as wispy arches in the hotter corona. Simultaneous pictures of chromosphere and corona made by Skylab demonstrate that nearly all light emitted by the hot corona comes from loops that trace out patterns of magnetic lines of force rooted in bright, active regions in the chromosphere.

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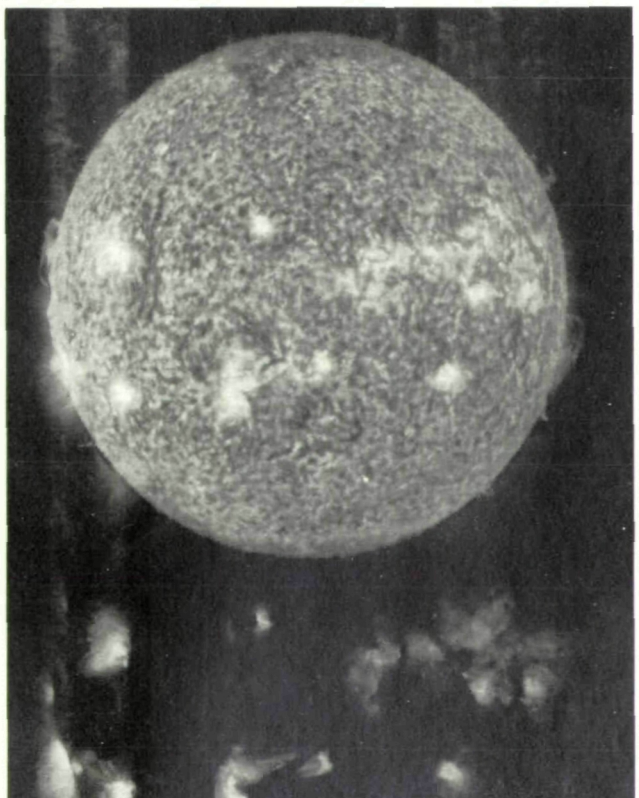

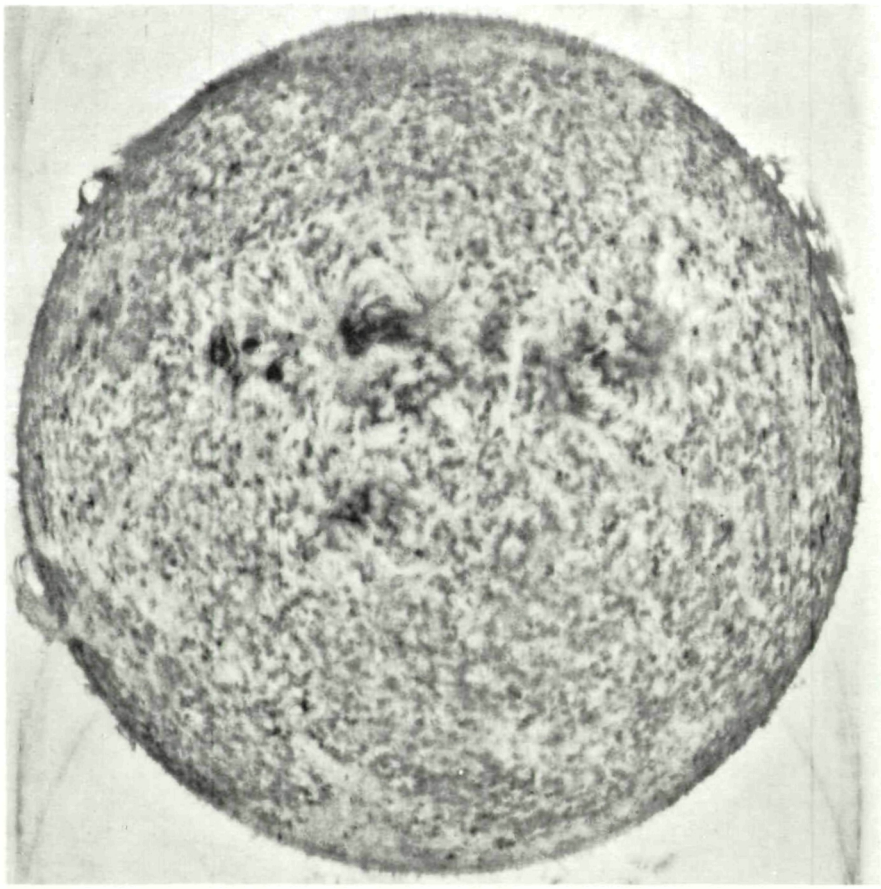

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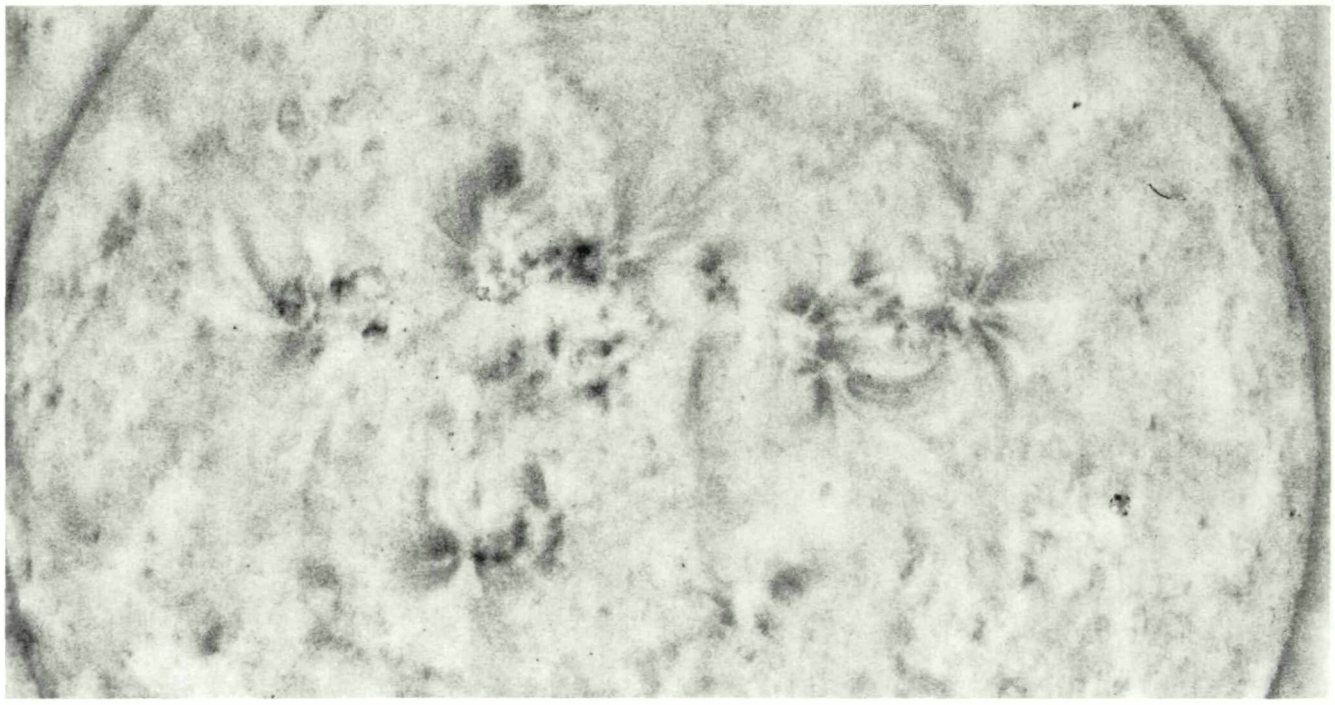
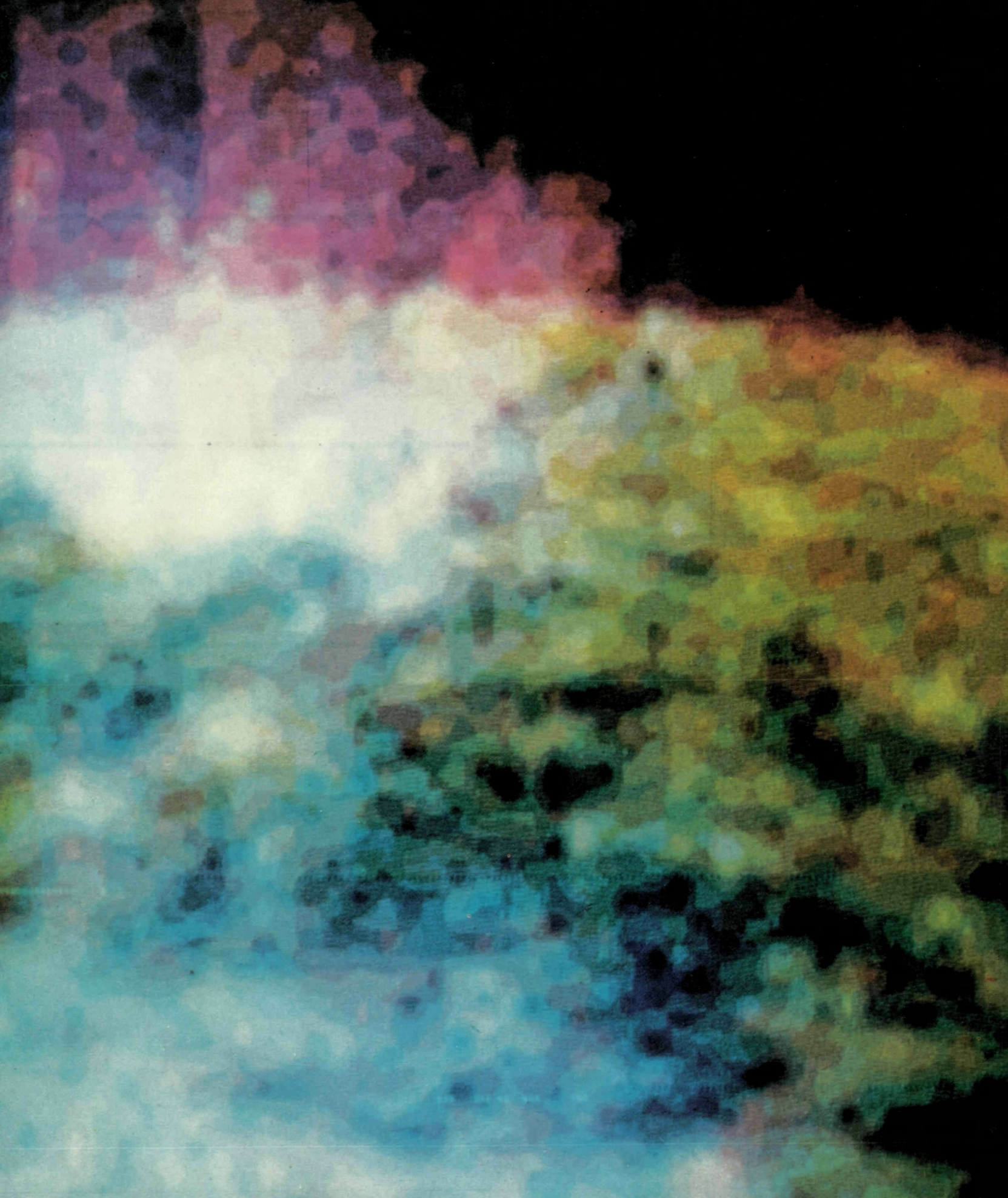


LIKE CHARCOAL PORTRAITS, these photographs of the Sun in ultraviolet light delineate fine details and relationships undocumented before Skylab. All are negative prints; blacker features are in reality brighter on the Sun. The chromosphere (1) is covered by an irregular mesh of bright, emitting spicules. The network fades at polar regions of the Sun, where larger spicules jut out to roughen the solar limb; it is also distorted by centers of activity in bands of middle latitude. Ghostly prominences hang high above the limb around the edges of the Sun, shaped and supported by magnetic forces, made of chromospheric material too cool to be seen in the hotter views (2, 3, 4). A simultaneous photograph of the transition region (2) between chromosphere and corona samples a temperature shell so thin that certain features here appear especially sharp. The bright (black) ring around the Sun is an edge-on view of this layer.

2

4

At these heights and temperatures the network is fading, and the cool, dense prominence curled around the left lower solar limb in (1) appears as a white shadow that interrupts the transition ring. Fine brushes of lines sprout from bright chromospheric regions near the center of the disk, revealing the lower legs of magnetic loops that stand in active regions. The equatorial region of the Sun (3) samples coronal temperatures of about 10^6 K, where the network is no longer recognizable. Connecting active regions are higher, fuzzier parts of the same loops whose lower legs were seen in (2). At still higher temperatures of 2.5×10^6 K, (4) the corona shows bright (black) emission only from active regions—in complete loops that arch still higher above the Sun, enveloping the cooler arches seen in (1-3).



IMPRESSIONISTIC LANDSCAPE of an unseen, fiery world (1) was created by combining separate, ultraviolet pictures (2, 3, 4) made in wavelengths that isolate the chromosphere, transition region, and corona. Colors were added in computer reduction to label the distinctive layers of the solar atmosphere. Green in the composite view (1) came from the separate picture (2) that sampled the chromosphere at a temperature of about 20 000 K. It is marked by choppy clumps of spicules that form the boundaries of the chromospheric network. Extended brighter regions in (3) reveal the elusive transition region at about 150 000 K, higher and hotter than the chromosphere. The burning bush of curving lines is formed by magnetic loops whose roots are concentrated magnetic areas in the photosphere. Blue (4) is light from the corona at about 1.4×10^6 K, where hot and foggy outlines enshroud the active region loops.

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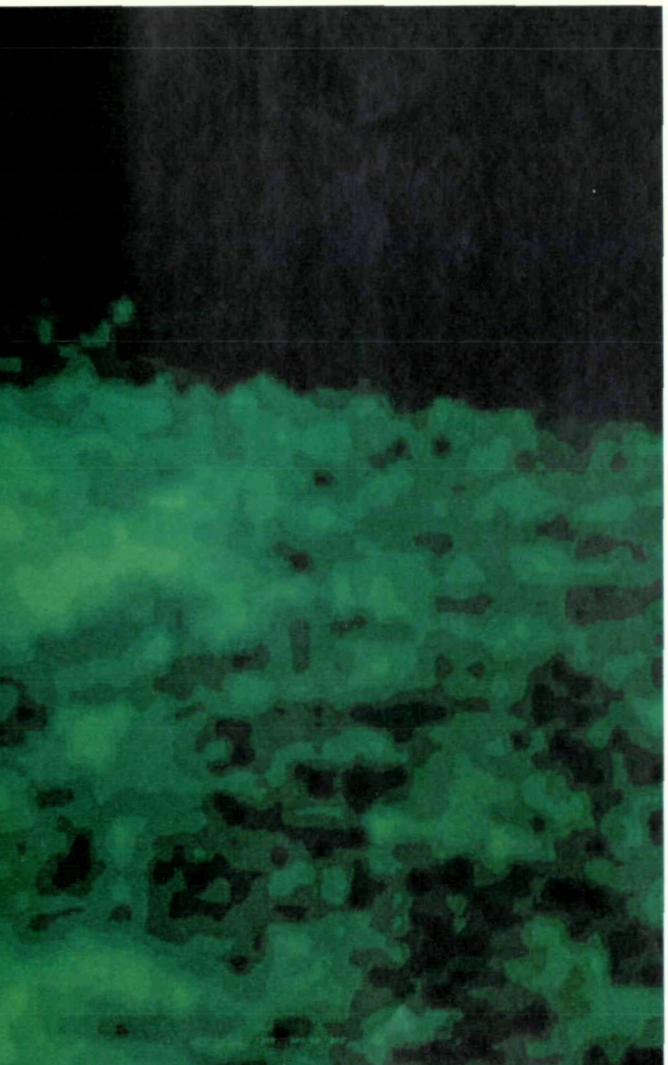

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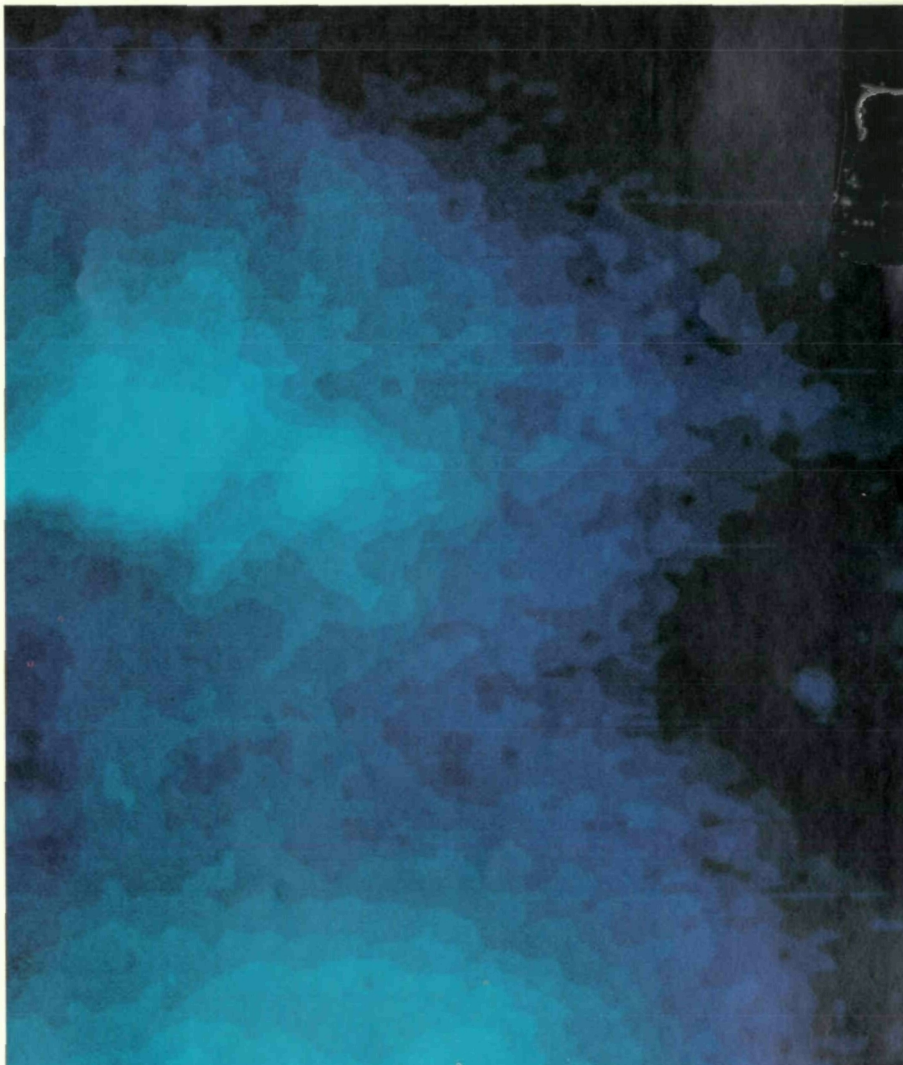

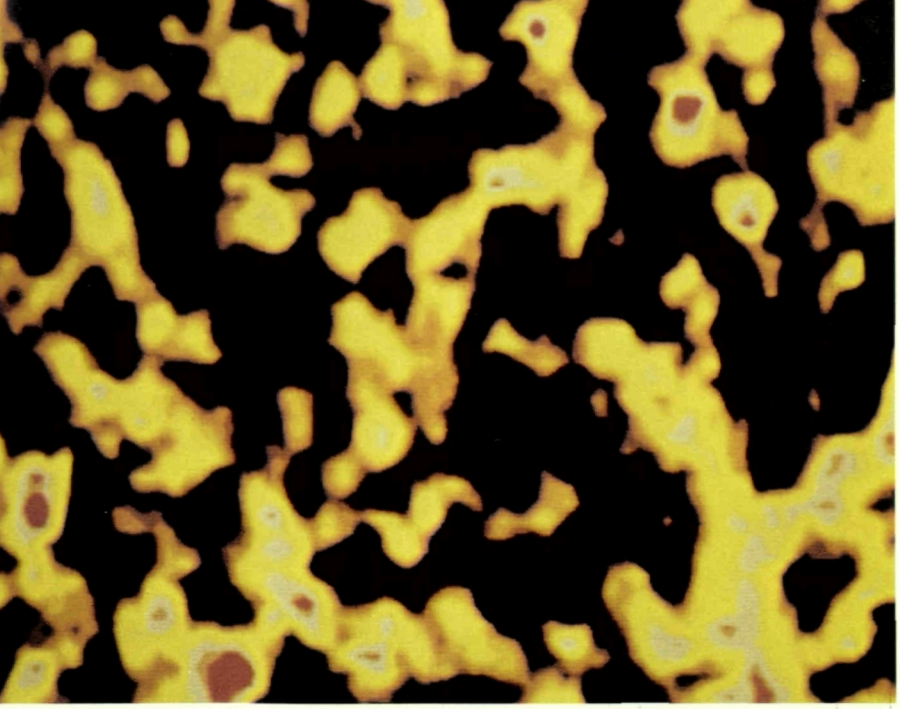

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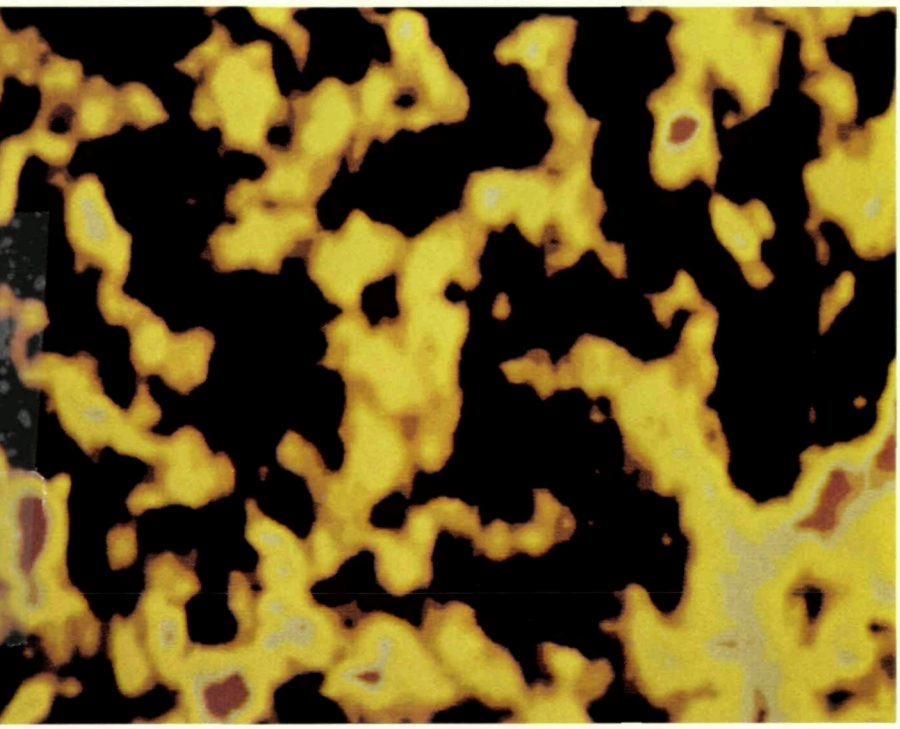

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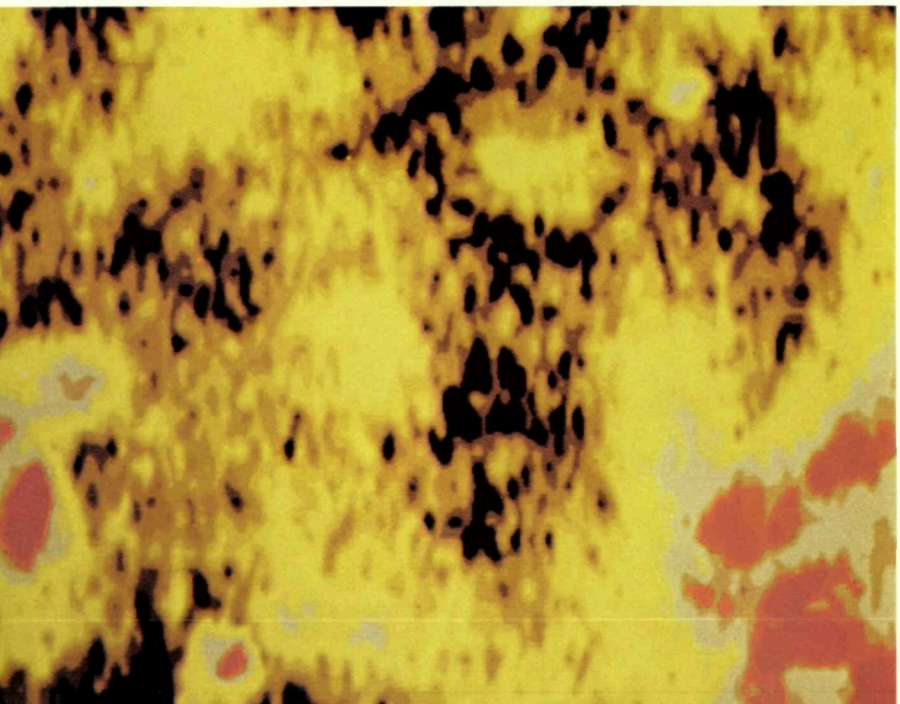

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THE CHROMOSPHERIC NETWORK fades and disappears with height in a set of ultraviolet pictures (1, 2, 3) made simultaneously in wavelengths that sample different layers of the same surface area of the Sun. Skylab's ultraviolet pictures for the first time defined the three-dimensional form of super-granule cells and mapped the ever-changing circulation patterns of the solar atmosphere.

In the chromosphere (1), where temperature is about 20 000 K, the network is distinct: bright segments of network cell boundaries appear in color-coded hues of yellow, brown, and white; centers of cells, where emission is less intense, are dark. A view of the same area at greater height (2) reveals a widening of the same network boundaries; in the transition region, where temperature is about 300 000 K, cell boundaries begin to spread and blend together. The same area (3) seen in coronal light at about 1.4×10^6 K looks vastly different. Spicule clumps at boundaries of the cells have spread at this height like the branches of an elm, and we now see only the blurred tree tops.

THE BRIGHT RING at the edge of the Sun expands in thickness over the solar pole. In this ultraviolet view (4) we see the transition region at about 600 000 K. The balding region at the top, covering the north pole of the Sun, is a coronal hole—an extended area where the coronal temperature drops. In the coronal hole the transition region, seen edge-on, widens appreciably, proving that the solar atmosphere thins and expands over the polar hole.

HIGH CHROMOSPHERE, seen in ultraviolet light, looks like a paint-spattered ball in this false-colored view (5). Bright spots show intense emission from small areas in a thin shell enveloping the Sun where the temperature is about 70 000 K. Specks of bright emission come from clumps of spicules around the boundaries of super-granule cells. Specks appear to crowd together toward the edge of the Sun, because of its spherical shape, producing the bright purple ring that here encircles the Sun.

THE ABRUPT JUMP in the height of the transition region over a coronal hole at the south pole of the Sun is plotted (6) in measurements made from another Skylab ultraviolet telescope, in the same spectral line as (4), also sampling temperatures of about 600 000 K. The dots plot individual measurements of the thickness of the transition region above the chromosphere. The height jumps from almost negligible thickness to about 12 000 km (the diameter of Earth) over the coronal hole. Beneath the plotted points is an ultraviolet picture of the corresponding region of the Sun, seen at coronal temperatures of about 1.4×10^6 K. The coronal hole appears as a dark gap in the otherwise white emission.

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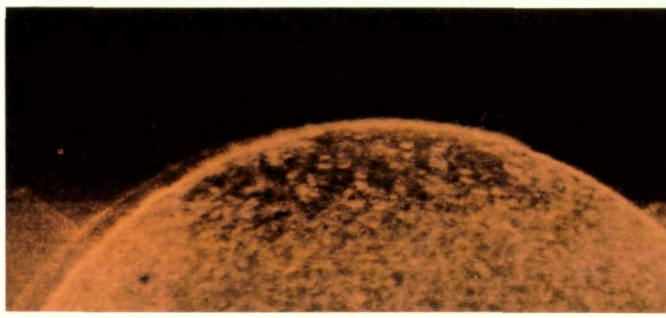

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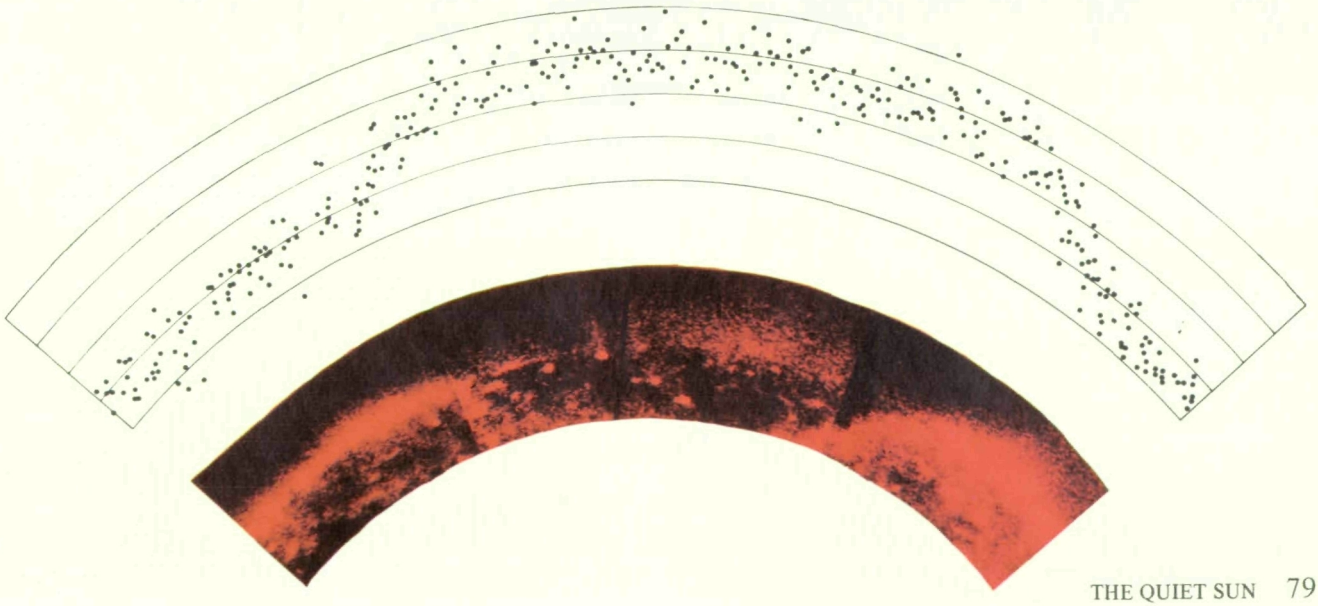

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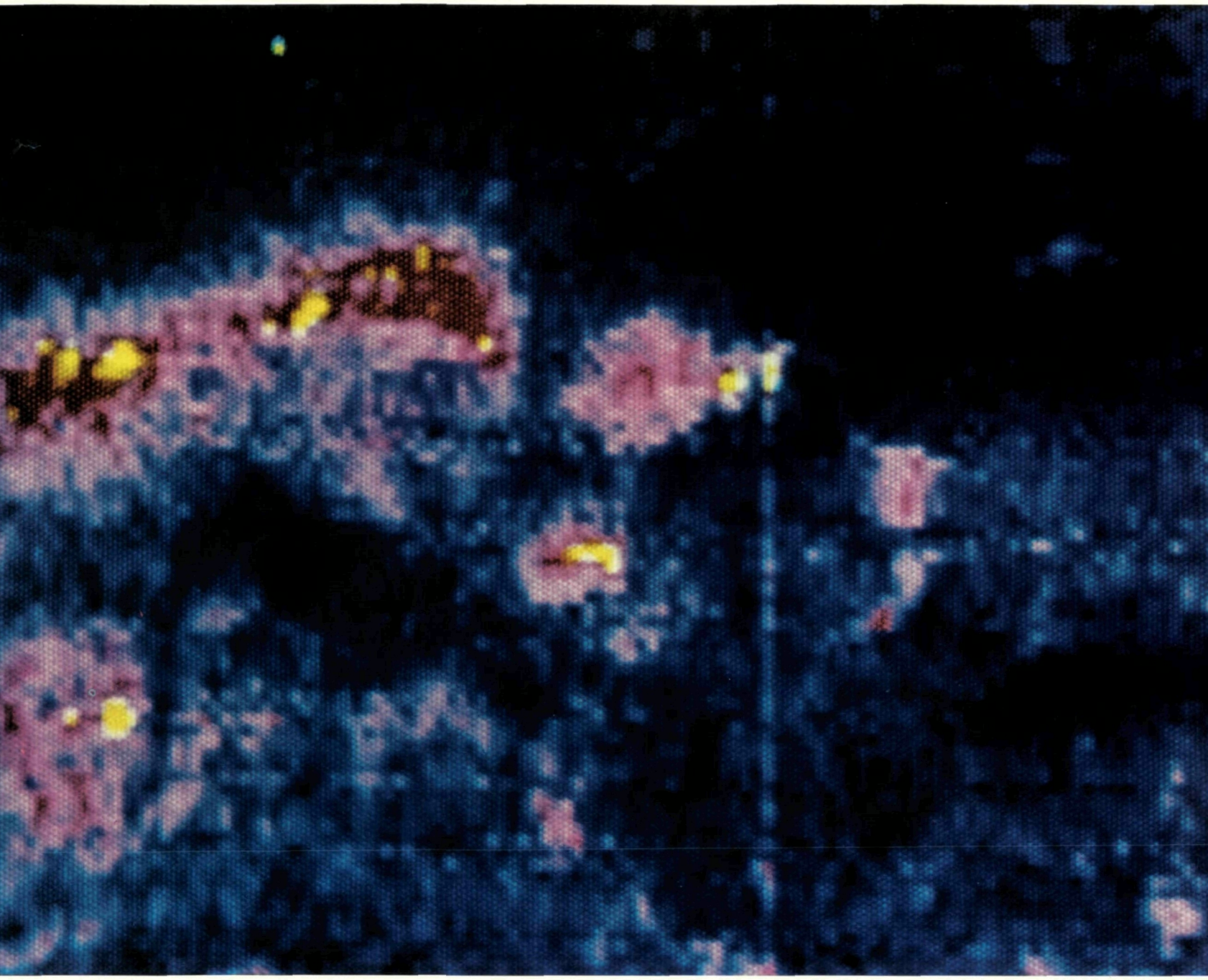
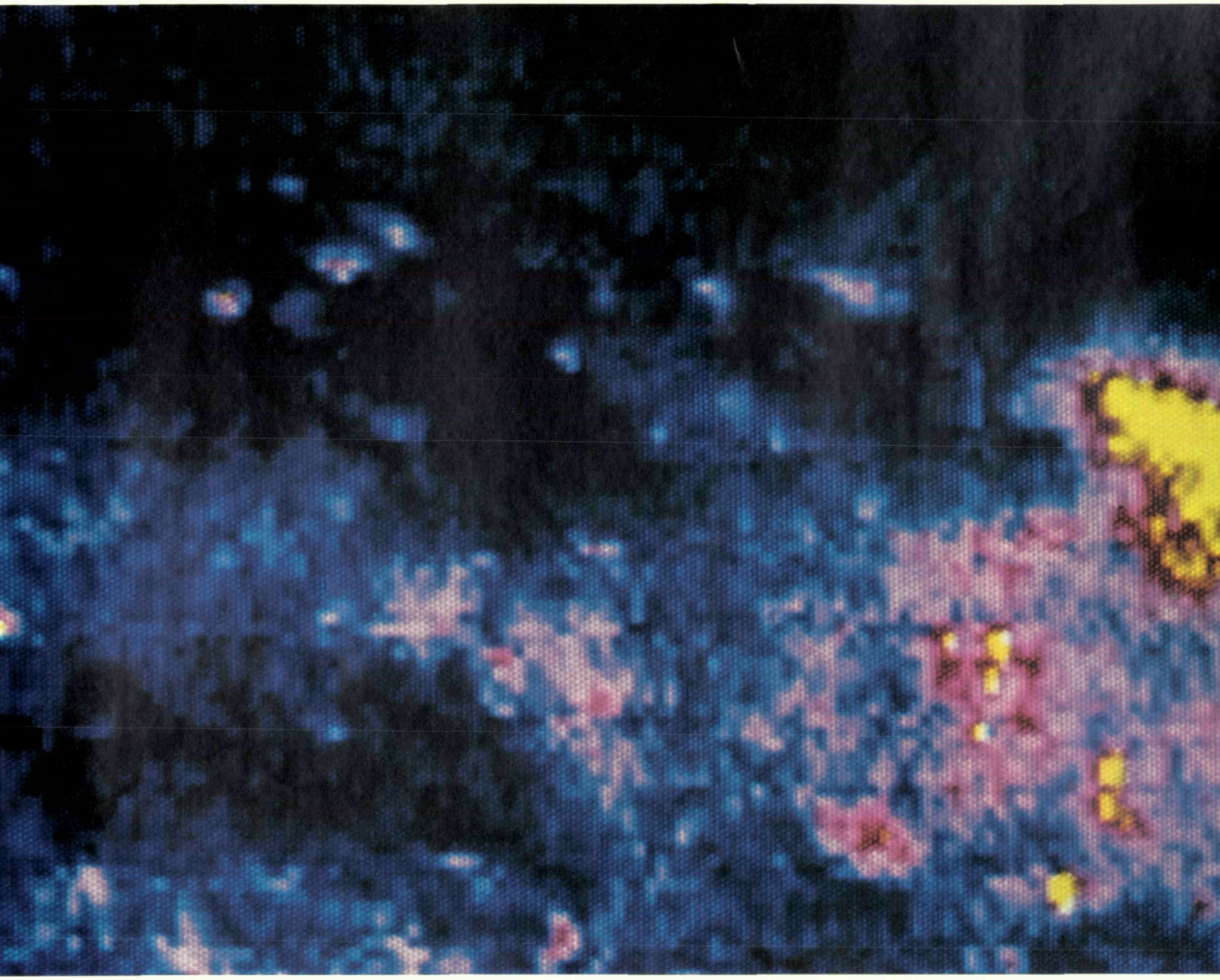
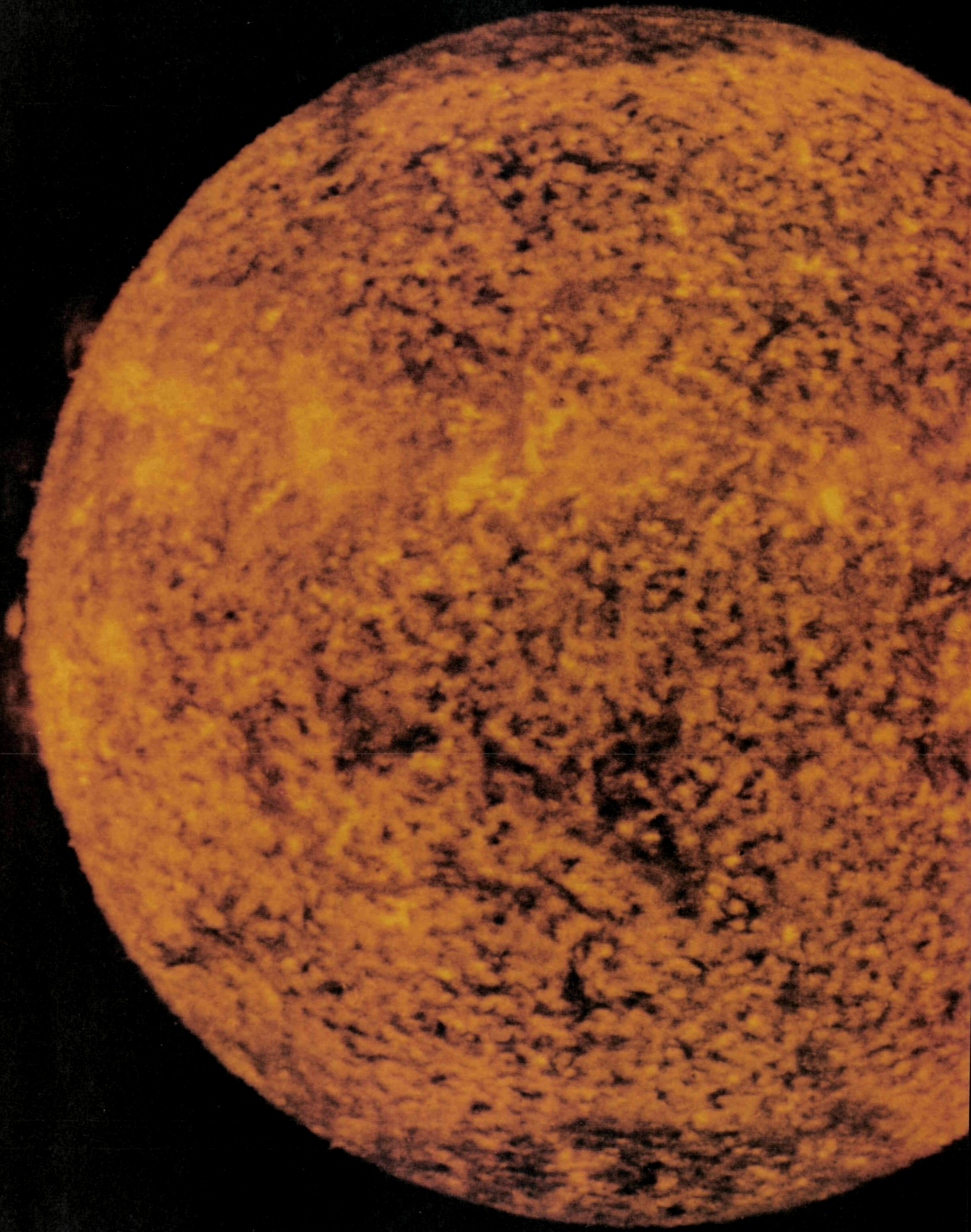


AT THE POLES OF THE SUN

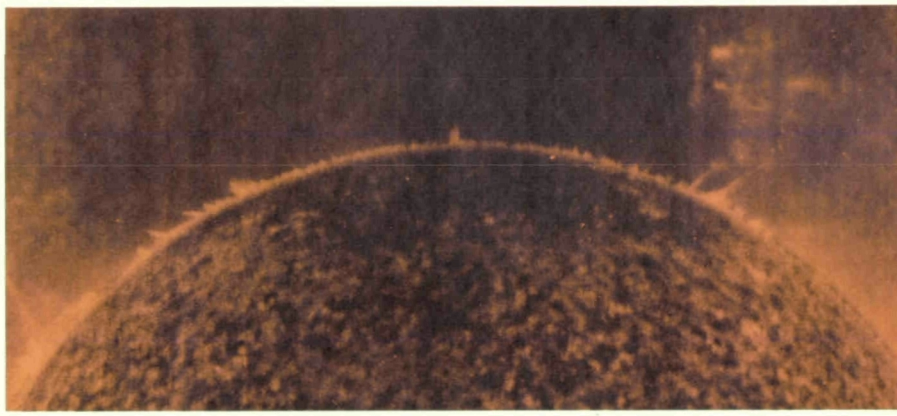
The north and south poles of the Sun—the ends of the axis on which it constantly spins—were revealed in new clarity in Skylab's ultraviolet and X-ray views. From the ground, in visible light, they had always looked much like the rest of the Sun, although theory had hinted that they should follow slightly different rules. With the benefit of ultraviolet and X-ray eyes, Skylab scientists found, as did Earth's first Arctic explorers, that the Sun's polar areas were in truth a unique and different world: the abode of a new class of giant spicules never seen before and a vast area where the vertical



structure of the solar atmosphere is distended and stretched upward. Most important was a new appreciation of the polar regions as the domain of enduring holes in the corona—spreading bald spots in the outer atmosphere of the Sun where the normally constraining magnetic forces relax and open up to allow an unencumbered flow of solar particles into interplanetary space. In Skylab's extensive pictures of the poles were found the source of the delicate, flowing polar plumes that had been seen only in fleeting glimpses by past generations of astronomers at eclipse: polar plumes traced open magnetic field lines at the solar poles, and at their roots were bright points of coronal light.



POLES OF THE SUN appear in new perspective when seen in ultraviolet light as in this picture of the high chromosphere made in a spectral line of ionized helium by one of Skylab's telescopes (1). In the photosphere and lower chromosphere the poles seem little different from the rest of the surface of the Sun. However, at a higher level corresponding to temperatures of 30 000 to 90 000 K, we see the balding zones at either pole where the bright chromospheric network abruptly ends, much as trees stop at timberline. These polar caps are long-lived coronal holes, where coronal temperature and density suddenly drop.



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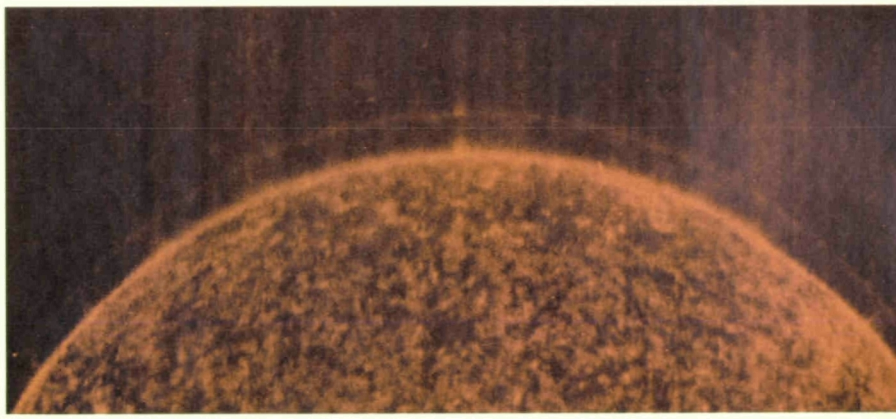

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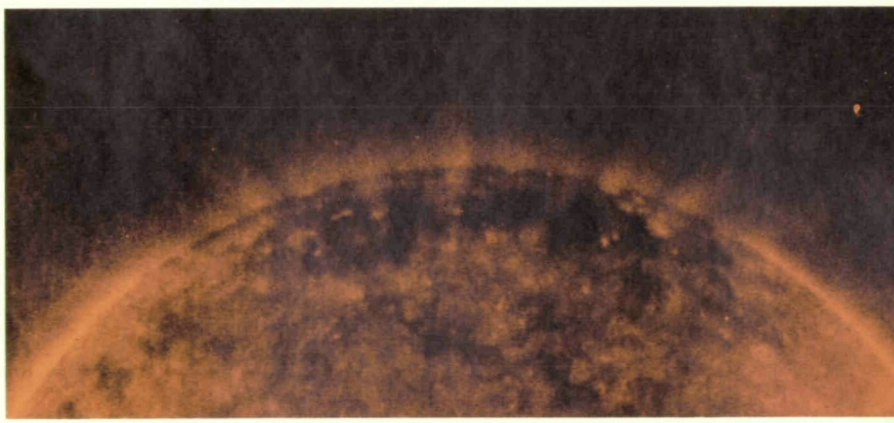

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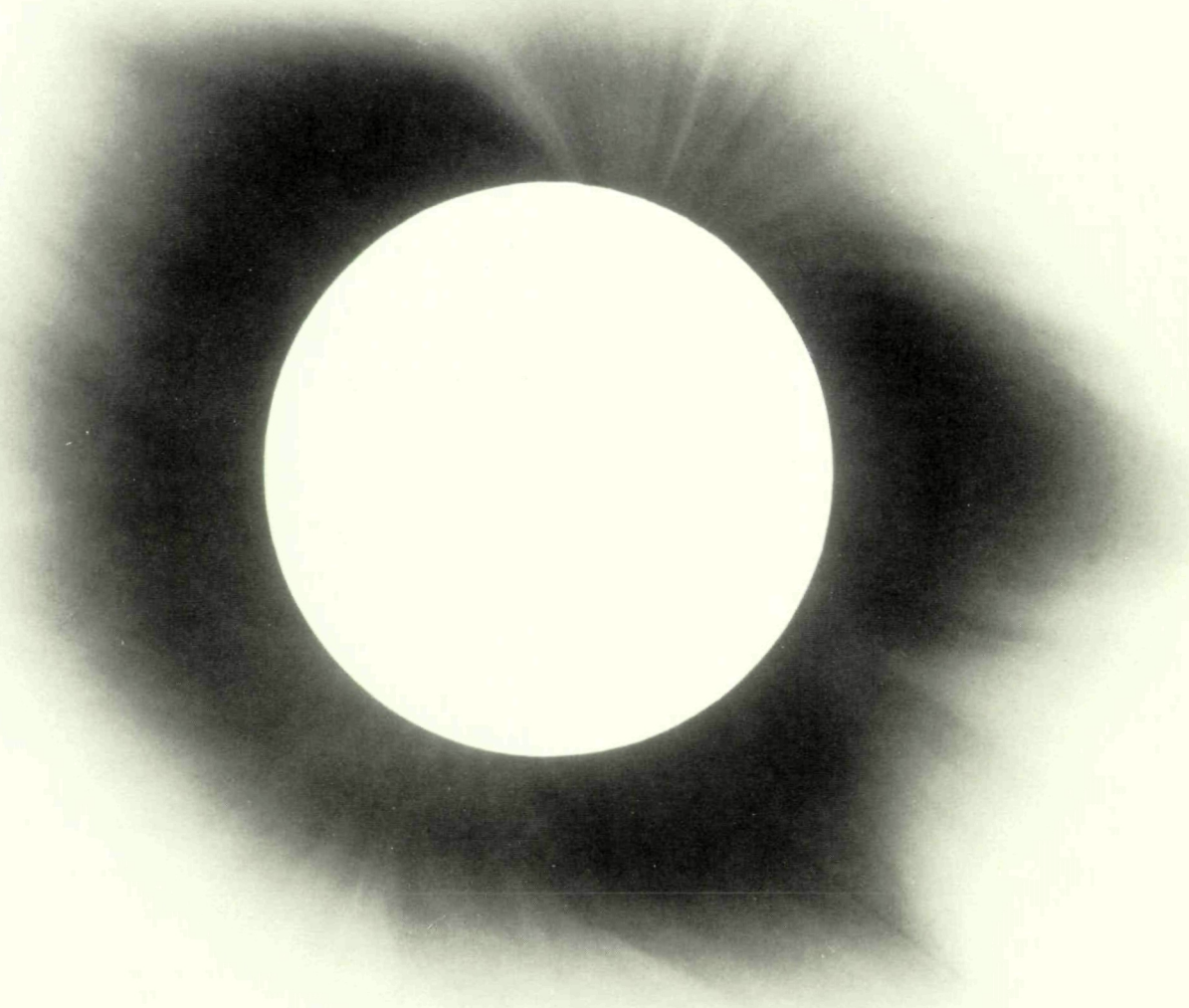
THE POLAR ATMOSPHERE of the Sun is dissected in three views made of the same area in different ultraviolet wavelengths.

(2) In the upper chromosphere, silhouettes of bright spicules jut up to give the Sun a ragged edge. Some are unusually large and were called "macrospicules" by Skylab solar scientists who first saw them in ultraviolet pictures like this. Most of the spicules and macrospicules do not rise vertically from the surface of the Sun but are inclined to either side, following solar magnetic fields that emanate from the polar coronal hole.

(3) Spicules and macrospicules fade from view at the higher temperatures of the transition region. In the polar hole there now appears a pattern of bright points of light.

(4) Polar features are most distinct in coronal light. The polar hole, seen less distinctly at lower levels, is dark and sharply bounded; at its edges the bright shell of coronal light seen around the limb of the Sun abruptly fades. In the hole, bright points seen in the transition region are now revealed as the bases of polar plumes that shoot up like searchlight beams into the void above.



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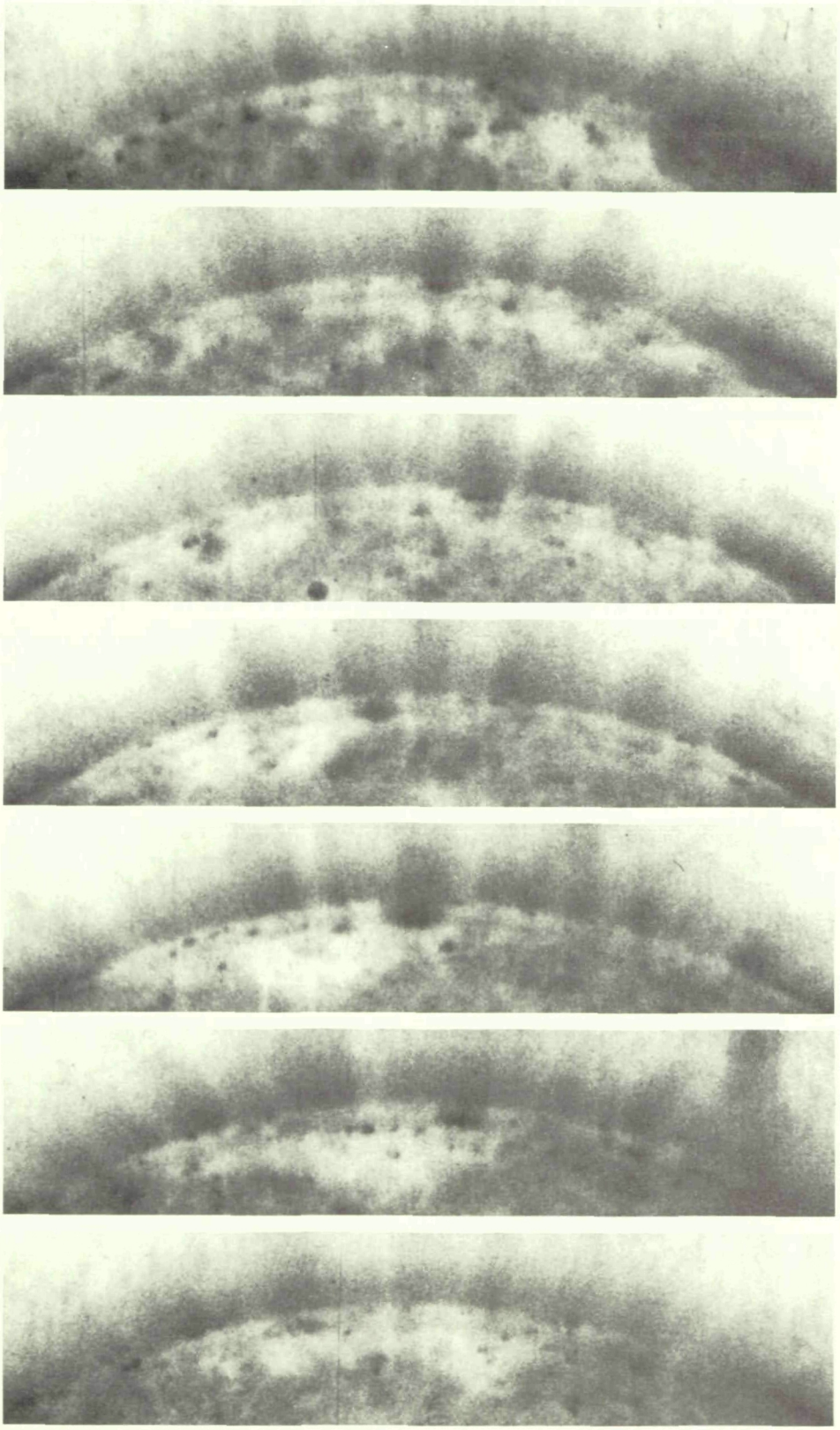
SKYLAB GETS TO THE BOTTOM of an old question: What are the polar plumes seen in the corona at eclipse?

Long noted in photographs of the eclipsed Sun, coronal polar plumes spread outward from the top and bottom of the Sun, resembling lines of force around the poles of a bar magnet. For many years they were taken as evidence that the Sun had a central, permanent magnetic field, like Earth. Plumes are obvious in the photograph of the corona (1) taken at a total eclipse of the Sun in Australia in 1921, here printed as a negative. In a normal print, and to the eye, the polar plumes appear white, like the rest of the visible-light corona.

Skylab's ultraviolet views of the poles of the Sun (also printed as negatives (2)) traced the plumes back to the surface of the Sun to find their source: bright points in coronal holes. The bright points are regions of concentrated magnetic field. Plumes are outflowing streams of coronal gas that follow magnetic lines of force originating in these separate magnetic regions.

The bright points and plumes are not lasting features of the Sun. The sequence (2) tracks the behavior of polar plumes with time. Each picture, top to bottom, shows the same area of the solar pole, separated in time by about 1 day. In all, 6 days are shown. Individual plumes rotate with the Sun and may persist for several days.



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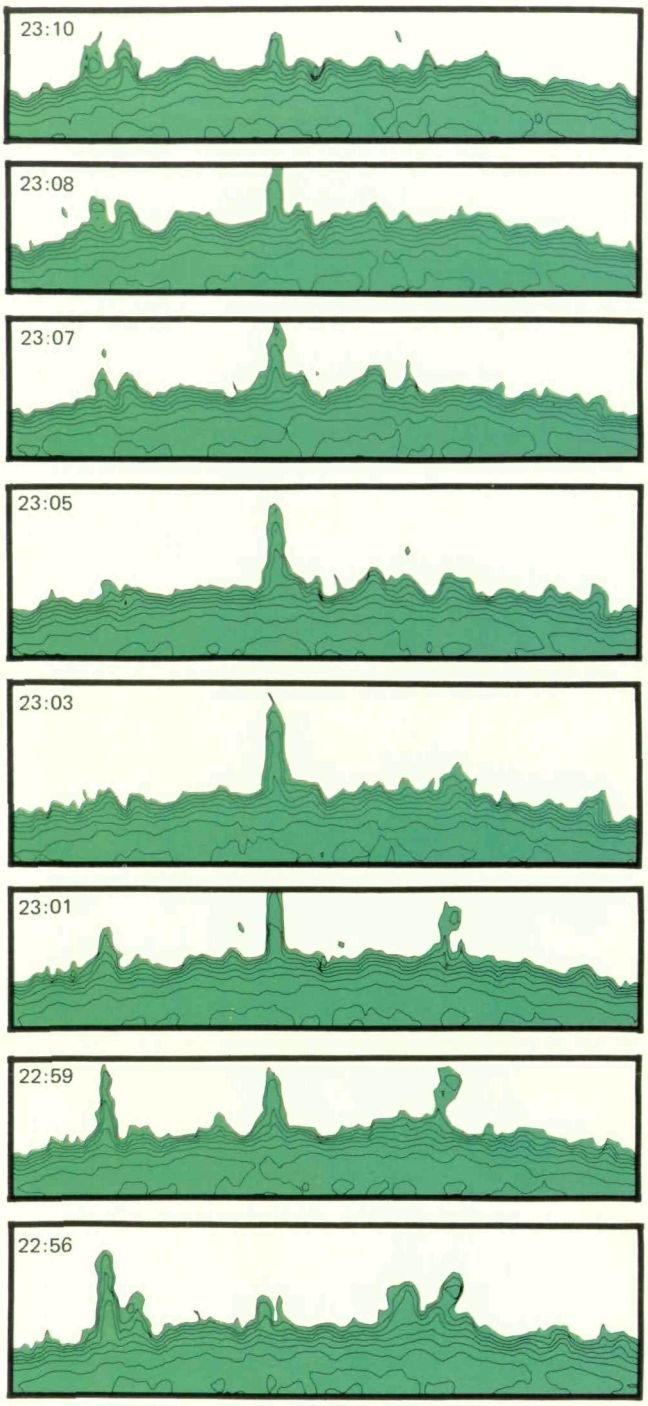

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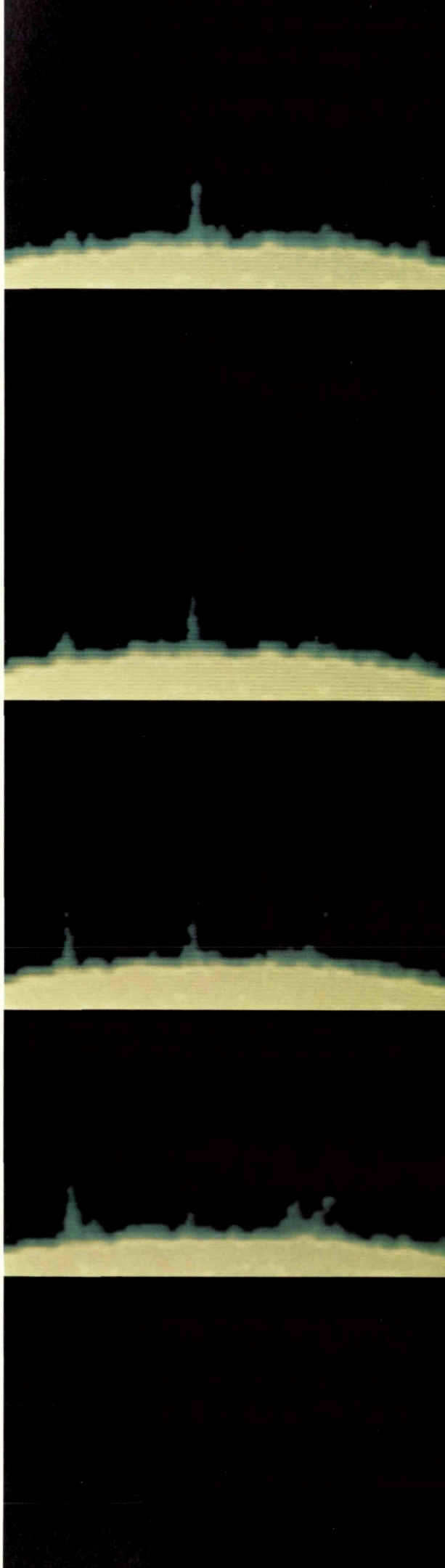

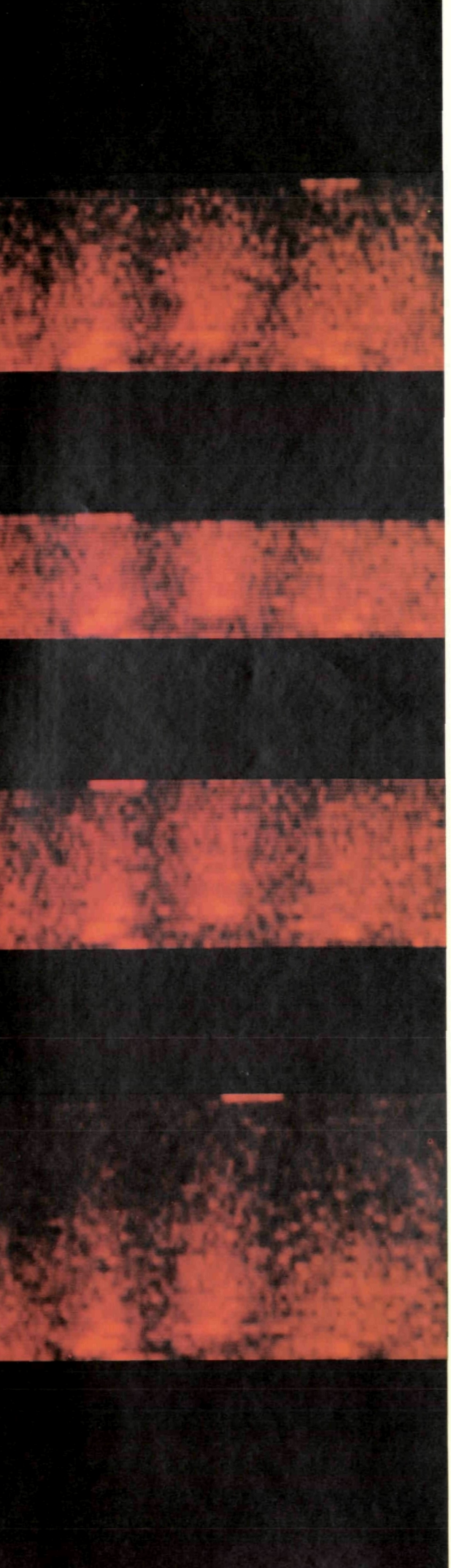

GIANT SPICULES, found only in the Sun's polar cap, were not fully recognized before Skylab's detailed ultraviolet coverage of the Sun. Wider, higher, and longer lived than the smaller jets that fence in the super-granule cells, macrospicules are a new and separate feature of the Sun. Some rise to more than 40 000 km above the solar surface and are twice as wide as Earth. Unlike smaller spicules that rise and fall in 5 or 10 min, macrospicules last as long as three-quarters of an hour. They are parts of the churning chromosphere, at temperatures of about 50 000 K, thrown upward at more than 150 km/s, only to fall back again.

(1) At the Sun's north pole, macrospicules rise and fall like stormy waves dashed against a seawall. Here ultraviolet pictures made in rapid sequence are shown as intensity contours. Pictures are spaced about 2 min apart, covering 14 min in the life of the polar Sun.

(2) Simultaneous views of the polar chromosphere (green) and corona (red) were made in the ultraviolet to test for possible connection between macrospicules and coronal polar plumes, which here appear as wide bright red streaks. Green pictures were produced from the first four pictures in (1), spaced about 2 min apart. While both are features found only in the polar holes of the Sun, plumes and macrospicules seem to lead separate, unrelated lives.

(3) The Sun, seen with X-ray eyes, emphasizes the dramatic nature of the polar caps, and the relationship between bright points and the polar plumes. Bright emission in this picture, made with an X-ray telescope on Skylab, displays the corona at temperatures of about 2 million K. On this day the north pole of the Sun was tilted slightly toward us, and we see it more fully; the south pole, tilted away, is hidden behind bright loops of coronal light. The sharply bounded coronal hole at the north pole has opened up into a more extended hole that reaches downward across the solar equator, to regions of the Sun more than 1.5×10^6 km away.

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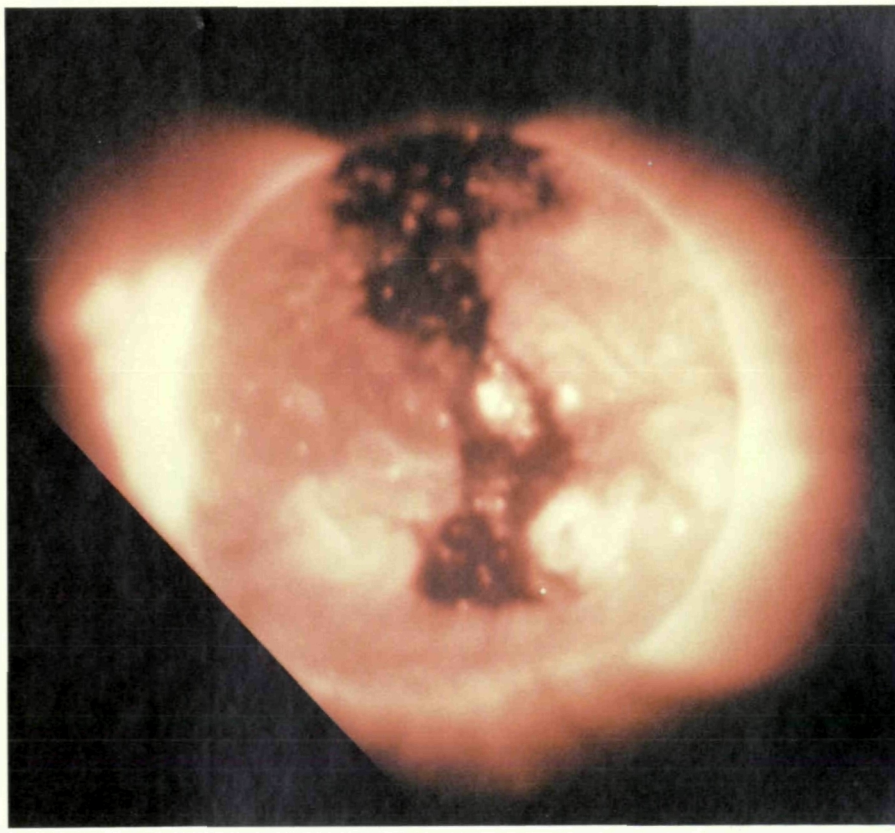
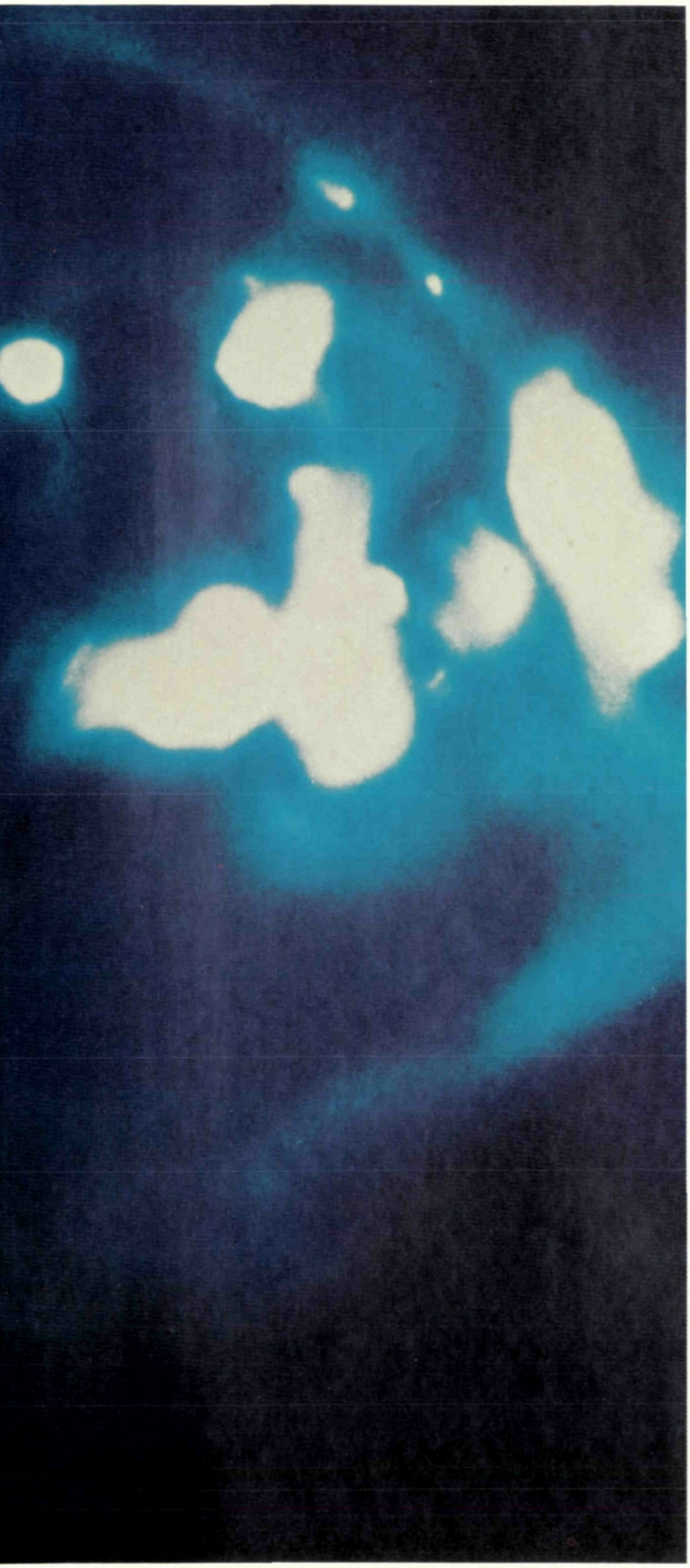


X-RAYS FROM THE SUN

Unlike in medicine, where they are used as a penetrating light source to make shadow pictures of solid objects, X-rays are studied in astrophysics for what they tell of the high-temperature gases that emit them—sources in the sky whose temperatures exceed about 10^6 K. An X-ray telescope pointed at the Sun will not see the cooler photosphere and chromosphere, but only the hot corona high above them. This offers a great advantage to the astronomer, for in X-rays he can observe the corona of the Sun without the need to block out the solar disk with a coronagraph. With an X-ray telescope he can see the corona all over the Sun, not just at the edges as at a total solar eclipse. Thus, X-ray observations of the corona offer an advantage like that of viewing a tangled forest from above, as from an airplane, where clearings and other features, hidden in ground-level, edge-on views, can be clearly seen. X-rays offer another valuable tool in solar observation: because they come from very-high-temperature regions, they provide a way of sorting out the details of the most intense features in the solar atmosphere, like the raging cores of solar flares, as we shall see in the next chapter.

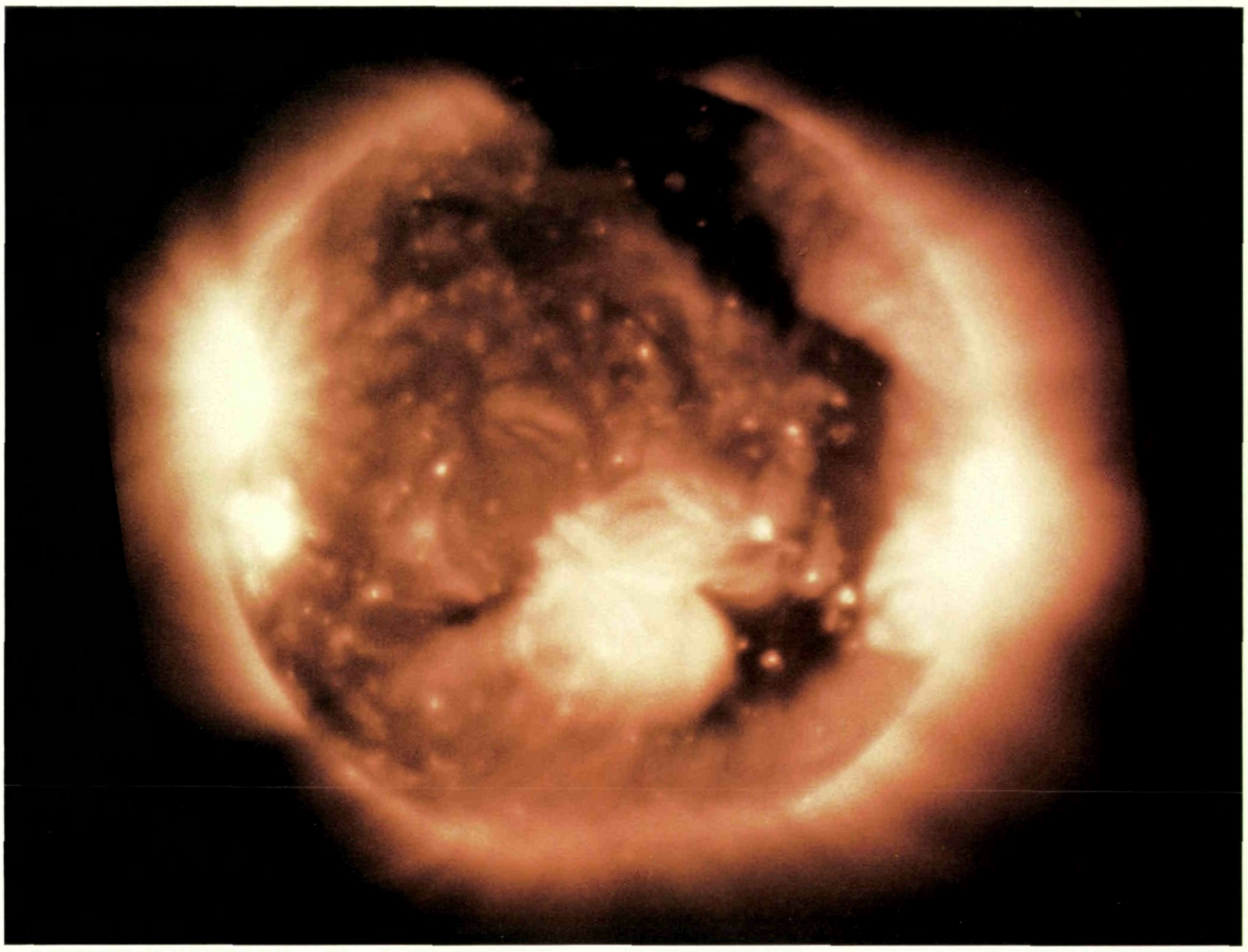


As in the ultraviolet, previous space experiments had demonstrated the power of X-ray observation of the Sun. In Skylab's arsenal were a number of X-ray instruments, including two high-resolution X-ray telescopes that took pictures of the Sun on photographic film as sharp and clear as pictures made in visible wavelengths from the ground. From these two telescopes came almost 60 000 nearly continuous pictures, revealing the structure of the corona as it had never been seen before. Subsequent analysis has underlined the importance of two new coronal phenomena, bright points and coronal holes, that after the Skylab missions are now seen to be among the most basic features of our Sun. Immediately obvious was the fact that the solar corona was built entirely of magnetic structures—a loose lacing of loops and arches the presence of which had only been hinted at before. There was no "quiet corona"; it was all magnetic loops. Where there were no loops, there was no corona. The view from above, in X-rays, had dissolved a long-held, mistaken view.

Metal filters in X-ray telescopes sort out X-rays of different strengths, allowing views of separate layers of the corona. The most energetic or "hardest" X-rays come from hot regions of 3 to 5×10^6 K; "softer" X-rays, come from slightly cooler areas of 2 to 3×10^6 K.

THE X-RAY PORTRAIT OF THE CORONA (1) was taken on the same day as (2) by one of Skylab's X-ray telescopes, when the Moon was not in the way. Features in (1) and (2) are clearly related. The X-ray portrait shows the less rarified regions of the corona, nearer the surface of the Sun, but over its entire face. We see at last the secrets of the Sun that have long been hidden from the generations of astronomers who spent months and years preparing and traveling to distant lands to see the Sun's corona for but a few minutes, and then could only guess its full three-dimensional form.

The eclipse corona in (2) was photographed in ordinary light from the ground on June 30, 1973, during a total eclipse of the Sun that took place while Skylab was in operation. The black disk in the center is the Moon, which



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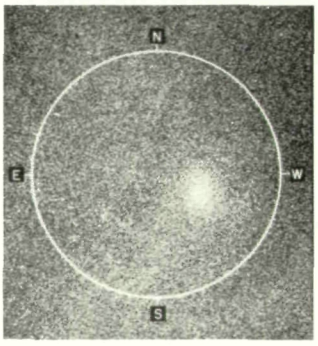

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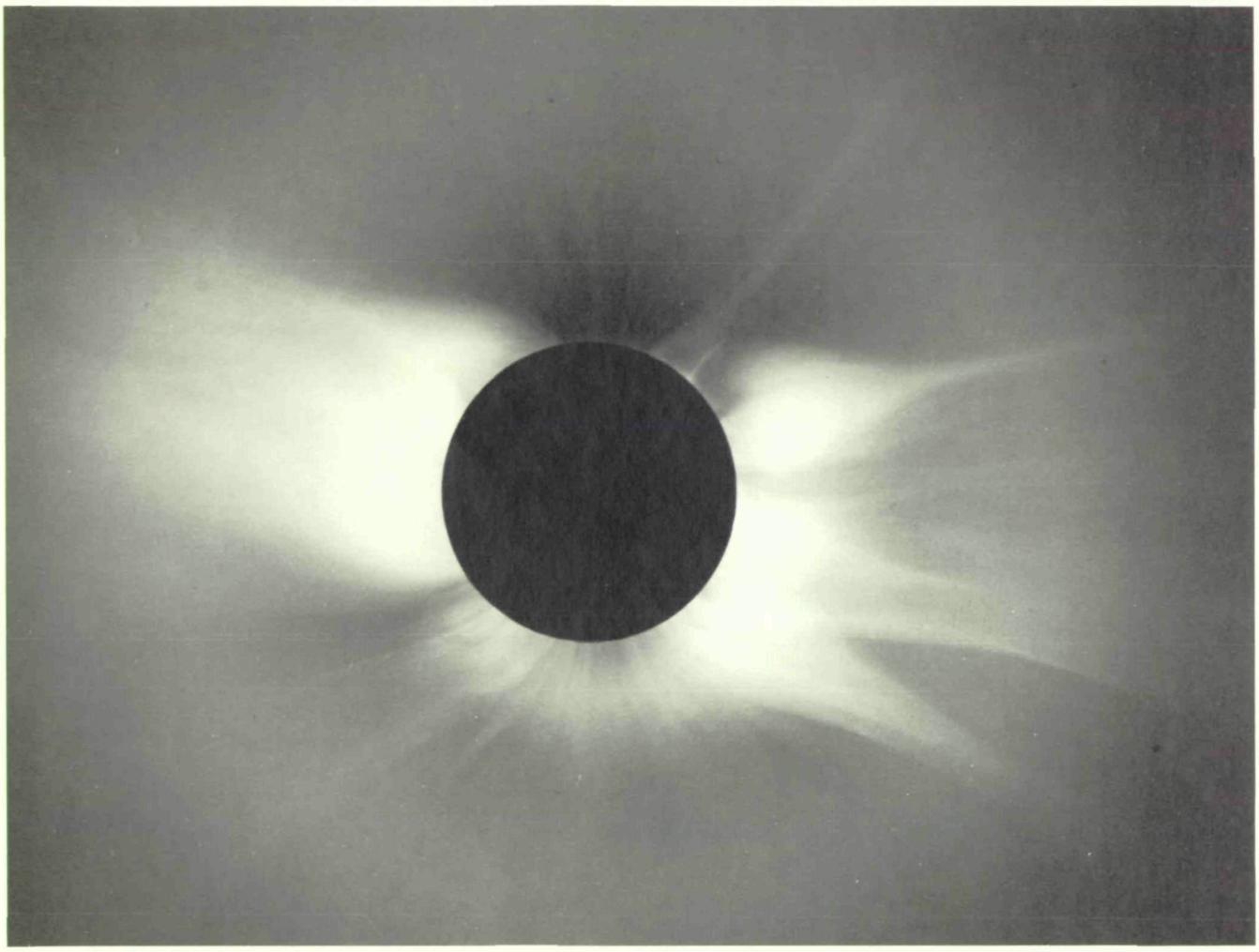
SKYLAB'S X-RAY TELESCOPES were not the first to see the solar corona, but instead were the culmination of a decade of progress in attempts at corona photography from rockets and unmanned spacecraft. These X-ray photographs of the Sun (3-6) taken from rocket flights between 1963

covers the bright photosphere and chromosphere, revealing the thin, hot corona that envelops the Sun. We see the beautiful and ethereal forms of the corona edge on, but the Moon stands between us and the parts of the lower corona that overlie the disk of the Sun, precluding comparison with chromospheric and photospheric features like sunspots, flares, and magnetic fields.



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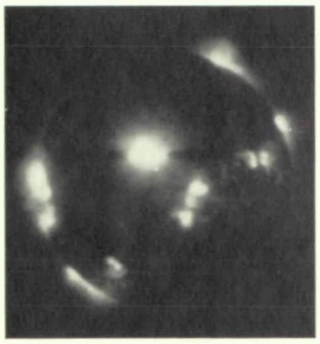

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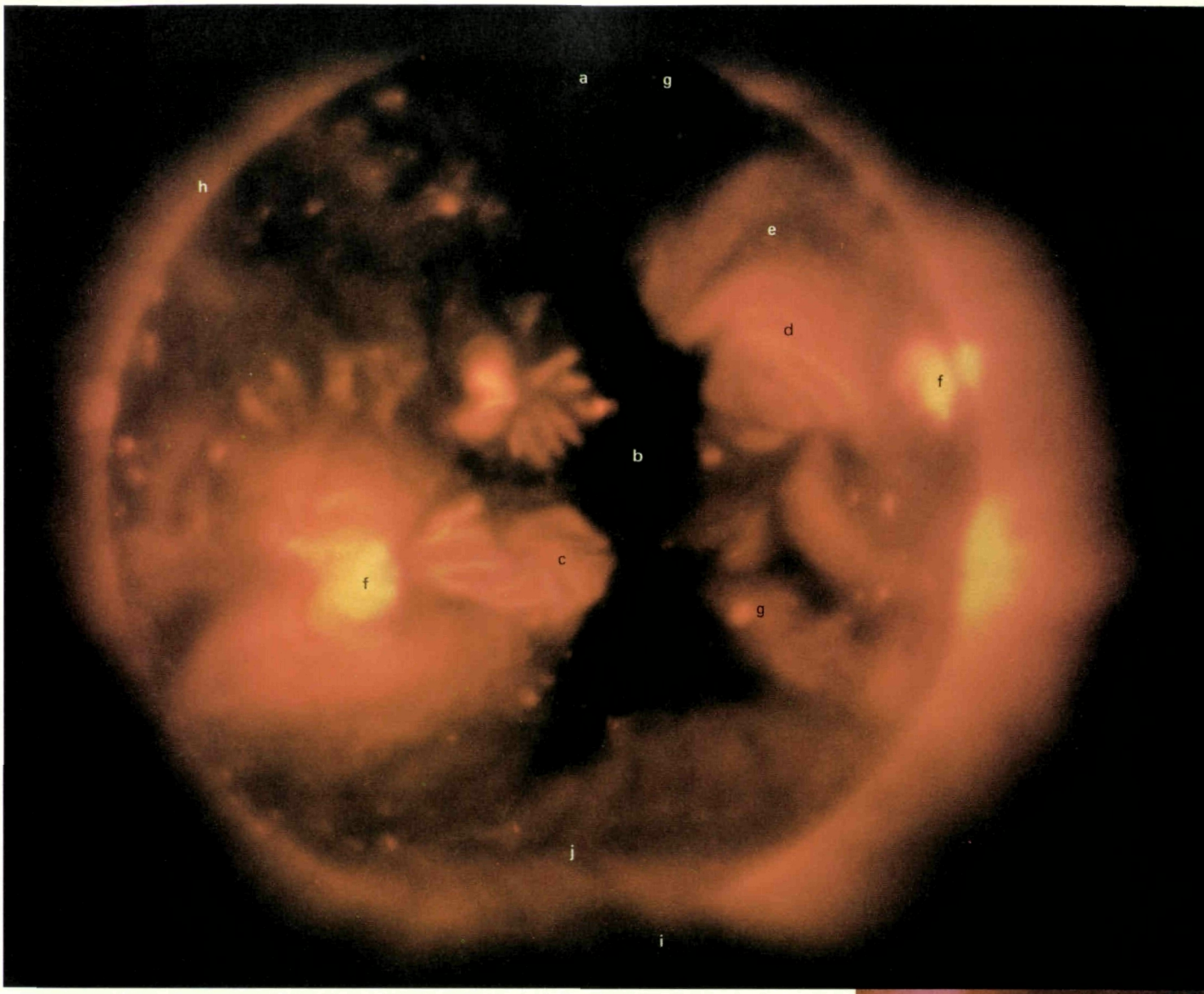
and 1969 chronicle the dramatic improvement in X-ray imaging of the Sun over this short span of time. The first attempts, like the first looks at the planets with Galileo's telescope, gave only coarse glimpses of the intricate details that later were revealed.



1

(1) AROUND THE EDGE OF THE SUN the X-ray corona floats like a hazy cloud, looking much like the lower corona at eclipse. Over the disk of the Sun, when seen as above, its intricate forms are at once revealed.

(*a*) In a coronal hole at the north pole X-ray emission seems utterly absent.

(*b*) Extended coronal hole stretches from the polar hole to about 45° south latitude, dominating the half of the Sun shown here.

(*c*) Tight loops lace surface active regions, connecting areas of concentrated magnetic fields on the solar surface.

(*d*) Larger loops connect distant active regions, thousands of kilometers apart on the solar surface.

(*e*) Large, hazy loops appear to link separated remnants of older active regions.

(*f*) Bright features in the X-ray Sun are active regions, related to sunspots, chromospheric plages, and concentrated magnetic fields.

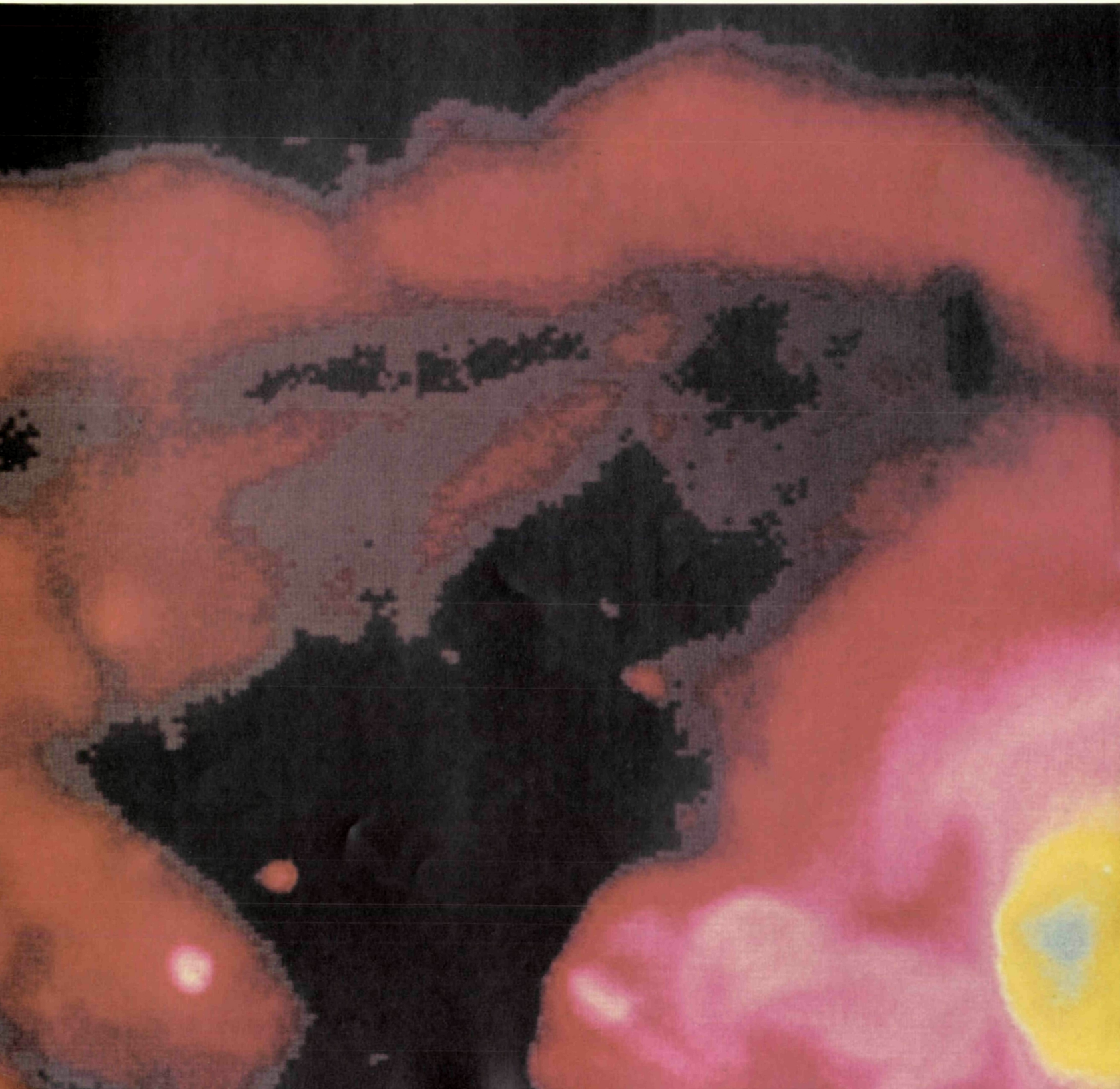
(*g*) Bright points appear over the entire solar surface, including the coronal holes.

(*h*) High corona above the unseen, opposite hemisphere of the Sun glows from behind the limb.

(*i*) South pole of the Sun is hidden from view by coronal loops in the foreground and by the slight tilt.

(*j*) Feathery, dark cavity marks a line of latitude where filaments lie in the chromosphere below.

(2) DISTANT CORONAL LOOPS blend to form red clouds on the solar horizon in this colored X-ray panorama of a region of the Sun near its north pole. A broad coronal hole spreads down before us like a black valley, dotted here and there by bright points that glitter like distant lights on a landscape. The bright yellow glow at right betrays the seemingly tranquil scene, telling of intense X-ray emission from an active region, bounded by hot pink loops that outline strong magnetic fields.



1

2

EERIE X-RAY PORTRAIT of the Sun (1) emphasizes the hottest, most intense parts of the corona—active regions that glow in this colored photo like coals in the night. Each active region is the seat of intense magnetic fields, where X-rays escape from heated gas trapped in magnetic loops that connect points of opposite polarity. Near the center of the solar disk (1) a curving zone of bright X-ray emission connects with circular patches of an even brighter active region to make a cosmic semicolon, nearly 300 000 km from dot to tail, that forms an archway through which Jupiter could be rolled.

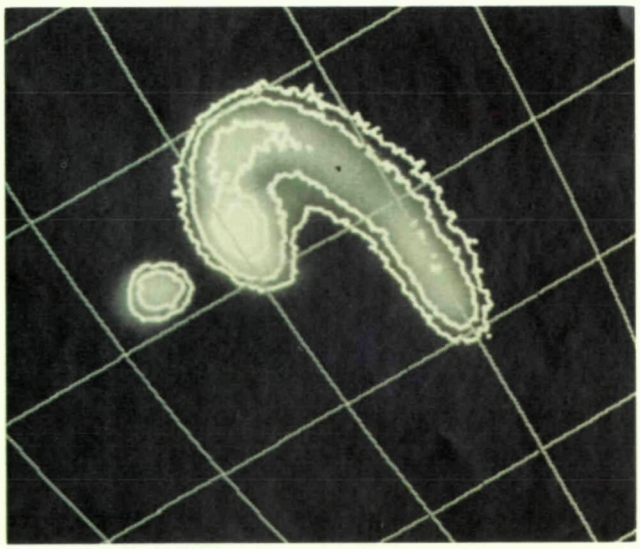
The same structure seen in an ultraviolet view (2) sampling similar temperatures reveals that the X-ray semicolon comes from a curved arcade of smaller loops.

The same Sun is seen in harder X-rays (3) by a telescope of Skylab that samples hotter temperatures. Here X-ray emission has been color contoured in computer reduction, and latitude and longitude grid lines have been added for accurate comparison with other solar data. The brightest coronal emission is colored white, and corresponds to temperatures in excess of 5×10^6 K.

Analysis of X-ray data from the giant curved arcade of loops at the center of (3) provides a temperature map (4), shown here as contours at several levels between 3×10^6 and 4×10^6 K.

3

4



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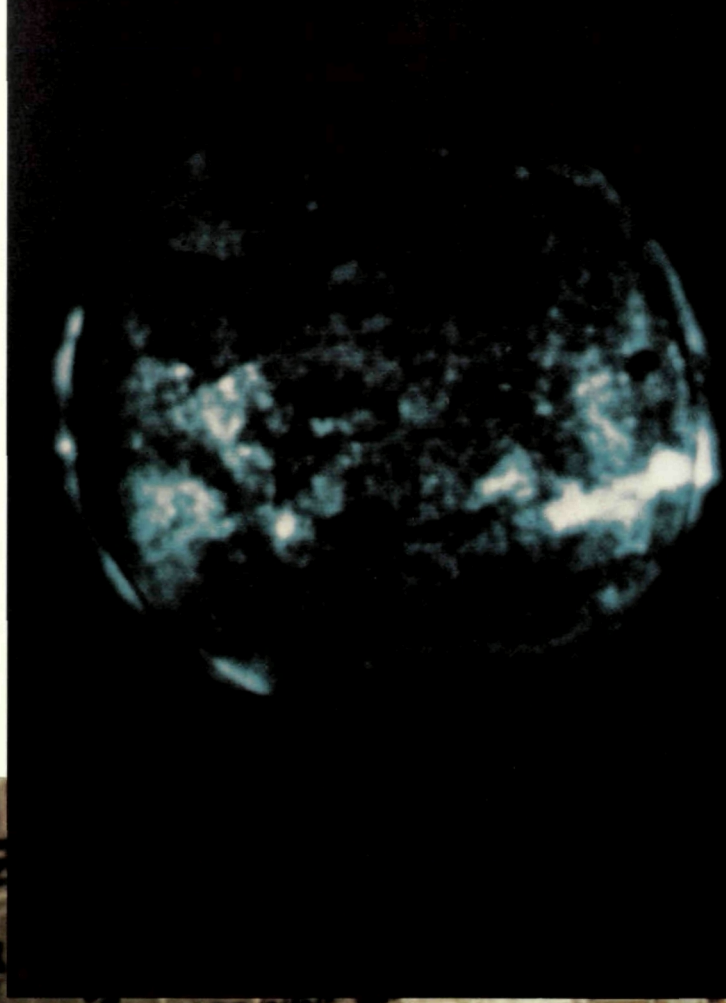
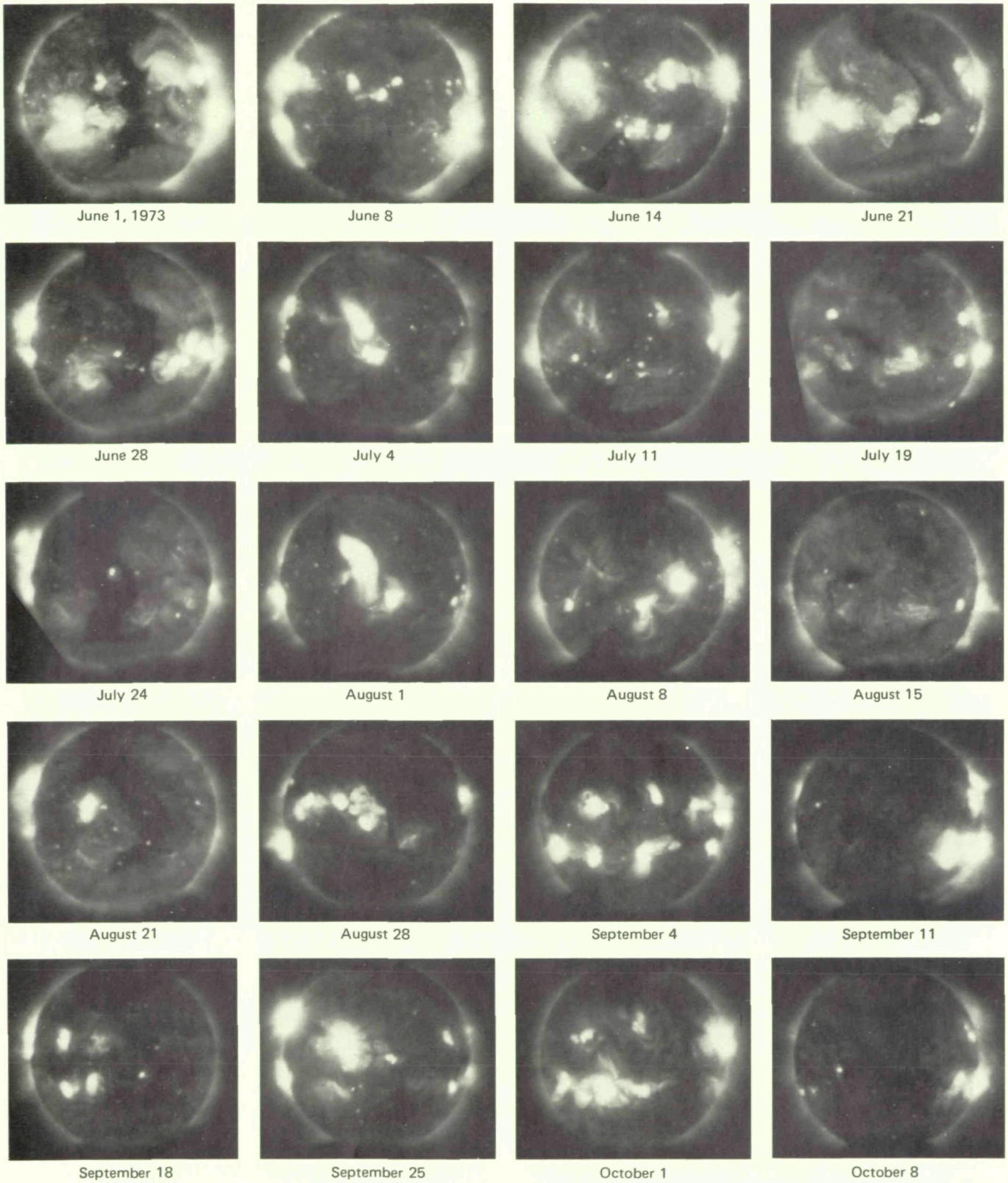


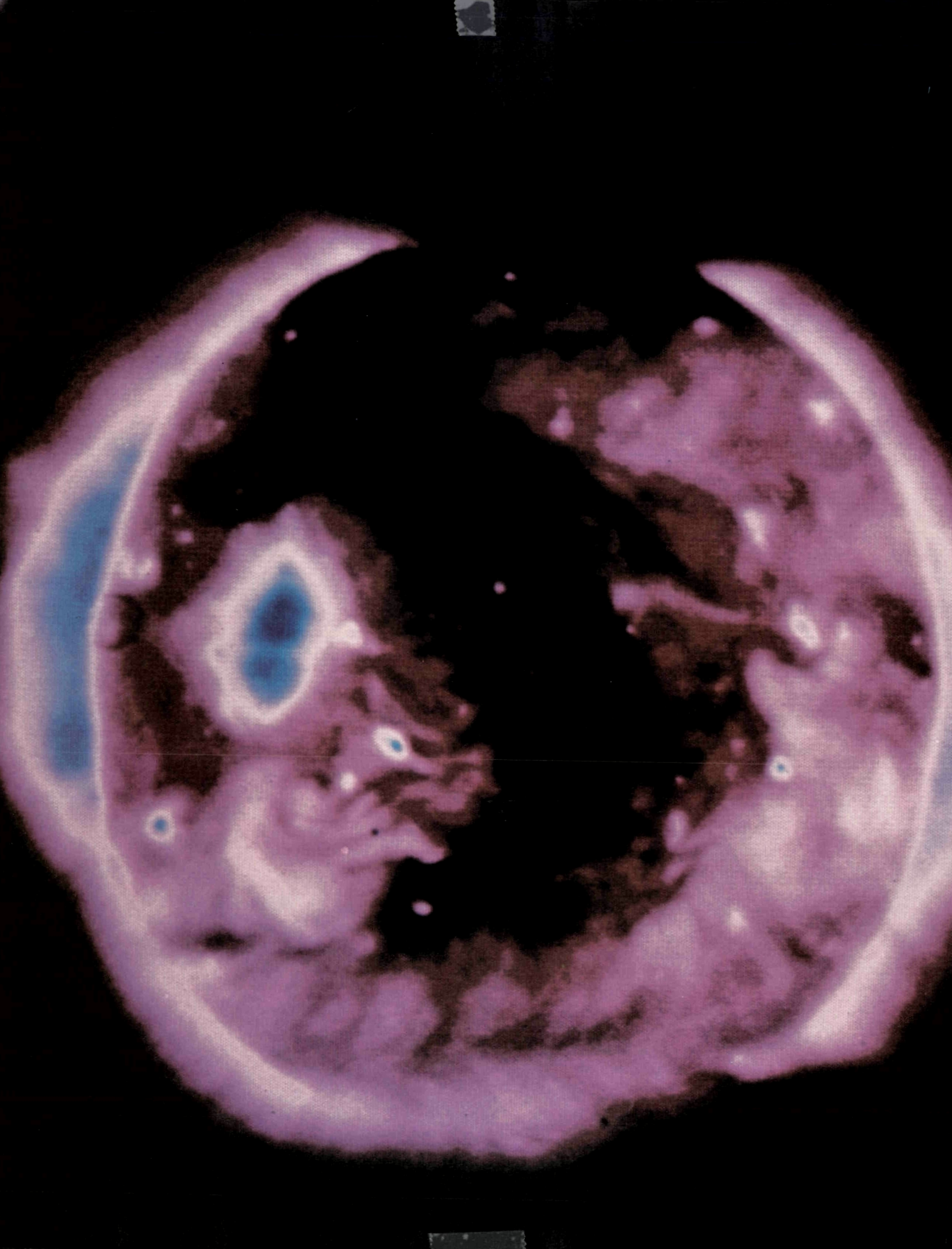
SKYLAB ASTRONAUTS were the first people in history who could watch features of the invisible ultraviolet and X-ray Sun and see changes as they were occurring. An extreme ultraviolet telescope on the spacecraft delivered a live television picture to the astronauts' solar control console to monitor the same levels of the solar atmosphere that were seen in the X-ray telescopes. To allow comparison with previous images, an ordinary Polaroid camera was carried up to Skylab by the second astronaut crew and attached to the video screen. New film that became available in the few weeks between the first and second manned Skylab missions made the sudden improvement possible.

(1) Astronaut Garriott photographs the video screen, producing an instant picture like (2), for an album of the first informal snapshots of the hidden layers of the Sun.

1



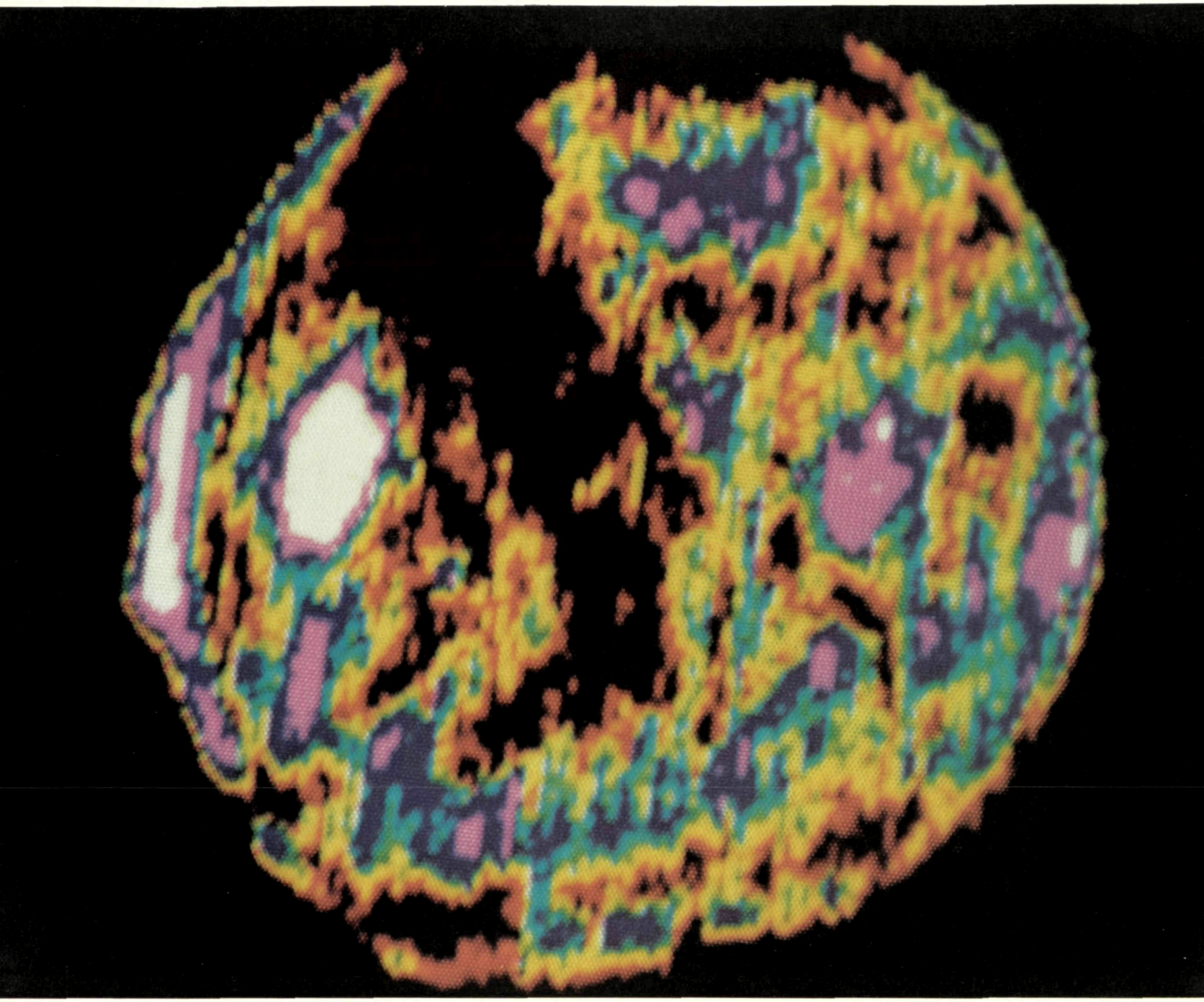
THE EVER-CHANGING CORONA is shown in these selected X-ray pictures that document five rotations of the Sun—about the first half of the full Skylab mission. The Sun rotates one-quarter of a turn in the 1-week interval between adjacent pictures; one row corresponds to one solar rotation of about 27 days. These glimpses are a sampling from more than 15 000 X-ray pictures that were made during the same period by this one Skylab experiment.



HOLES IN THE CORONA: THE OPEN SUN

Dark features called "holes" in the corona are extended regions where temperature and density are unusually low, and where solar magnetic field lines, normally arched and closed, open out from the Sun in nearly radial directions. They are one of the largest and, following the discoveries of Skylab, one of the most important features of the Sun.

Coronal holes are a recent discovery of solar physics; they are not readily apparent in the photosphere or chromosphere, and are subtle features in coronagraph data or in pictures of the corona made at the time of eclipse. In ultraviolet, and particularly in X-ray wavelengths, they stand out clearly as dark voids, nearly always present at the poles and often stretching down into the important middle latitudes of our Sun. They were first seen in scattered X-ray pictures of the Sun made before Skylab, and their possible relevance to conditions on Earth was soon surmised. But, it took thorough and continuous X-ray coverage to establish, beyond all doubt, that coronal holes are the source of the high-speed streams of solar wind particles that buffet the upper atmosphere of Earth, disrupting our own magnetic field and producing other lower atmospheric effects. This discovery, based on Skylab data, now stands among the most firmly established solar/terrestrial connections. Already it has been useful in the process of making daily forecasts of geomagnetic disturbances, of practical importance to man.



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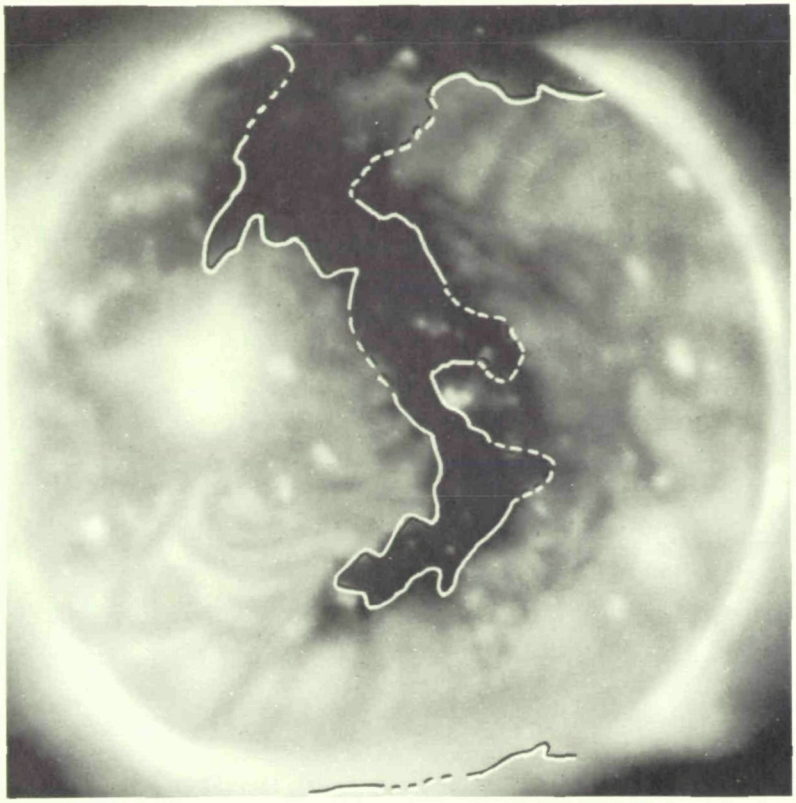
HOLES IN THE CORONA were first noted in X-ray pictures of the Sun made from rockets several years before Skylab. These important features had been missed by generations of eclipse watchers, for they are not easily recognized as holes in edge-on views of the corona. Since then, and with the help of Skylab's extensive coverage, they have been shown to be one of the most terrestrially important of all solar phenomena.

Skylab astronauts had learned to look for coronal holes on their live video display of the Sun in the extreme ultraviolet region. Image (1) was taken from their onboard video screen and transmitted to solar scientists in Houston. Computer reduction added the color contours and gave it a needlepoint character. Most obvious in this view of the ultraviolet corona is the large hole that begins at the north polar cap and extends down across the equator of the Sun, looking much like the boot of Italy on a map of the Mediterranean.

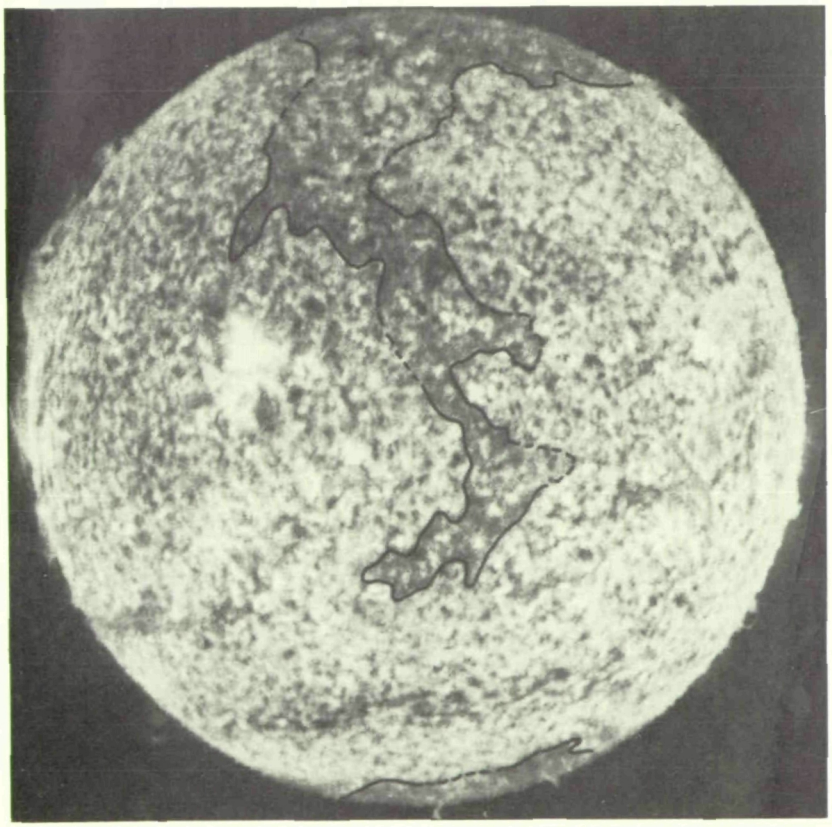
3

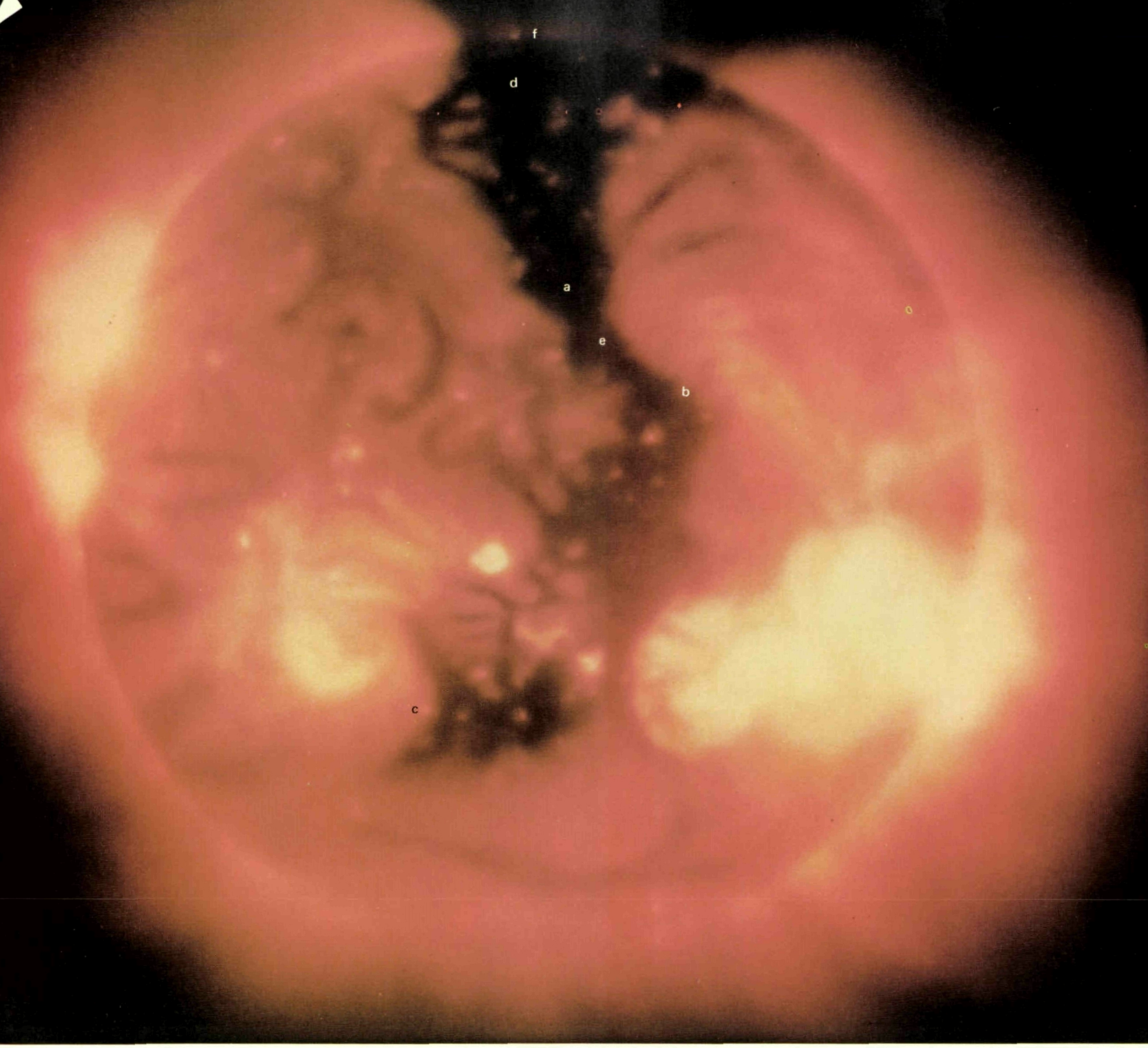


THE BOOT OF ITALY HOLE, and others like it, were watched continually by several Skylab telescopes. It is traced out on a picture of the high chromosphere (2) made in the ultraviolet one day after the preceding needlepoint view (1) was made. Coronal holes appear at this lower, cooler level of the solar atmosphere as fadings in the chromospheric network.

In an X-ray photograph of the Sun (3), made simultaneously with (2), the coronal hole has nearly identical form. As in (2), boundaries of the hole have been outlined for clarity.

2





1

(1) AS THOUGH PARTING A RED SEA, a long coronal hole opens up a path between billowing coronal arches to expose the cooler chromospheric surface below. Coronal holes are best seen in soft X-ray portraits like this one, where the steep walls of the hole can be seen in almost three-dimensional realism.

(*a*) Polar coronal hole connects to another extended hole—a winding chasm that reaches below the Sun's equator, more than $1\frac{1}{2} \times 10^6$ km away.

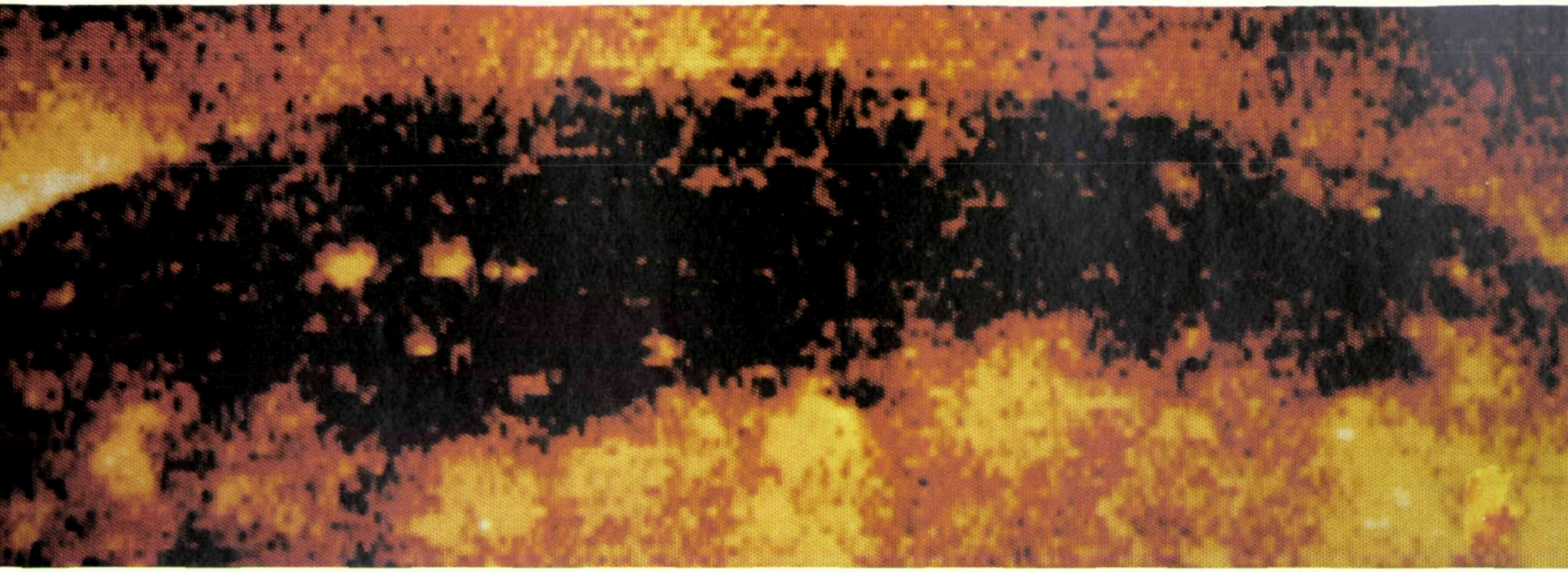
(*b*) Boundaries of coronal holes are steep-sided like canyon walls.

(*c*) Coronal holes are magnetically "open" features, as opposed to the "closed" or arched-over field lines seen elsewhere on the Sun. Magnetic field lines diverge at boundaries of the hole—none arch across the chasm. As a result, electrically charged particles in the hot solar atmosphere are free to escape from the Sun at coronal holes; elsewhere they are trapped in closed magnetic field lines and give the structured corona its distinctive form.

(*d*) Temperature within a coronal hole is about 10^6 K, two to three times lower than in active regions and about 50 percent lower than in surrounding "quiet" areas. Density is three times lower than in the neighboring corona.

(*e*) X-ray and ultraviolet emission is either very weak or absent altogether in holes.

(*f*) Polar plumes originate in coronal holes at the polar crowns of the Sun and are rooted in bright emission points.



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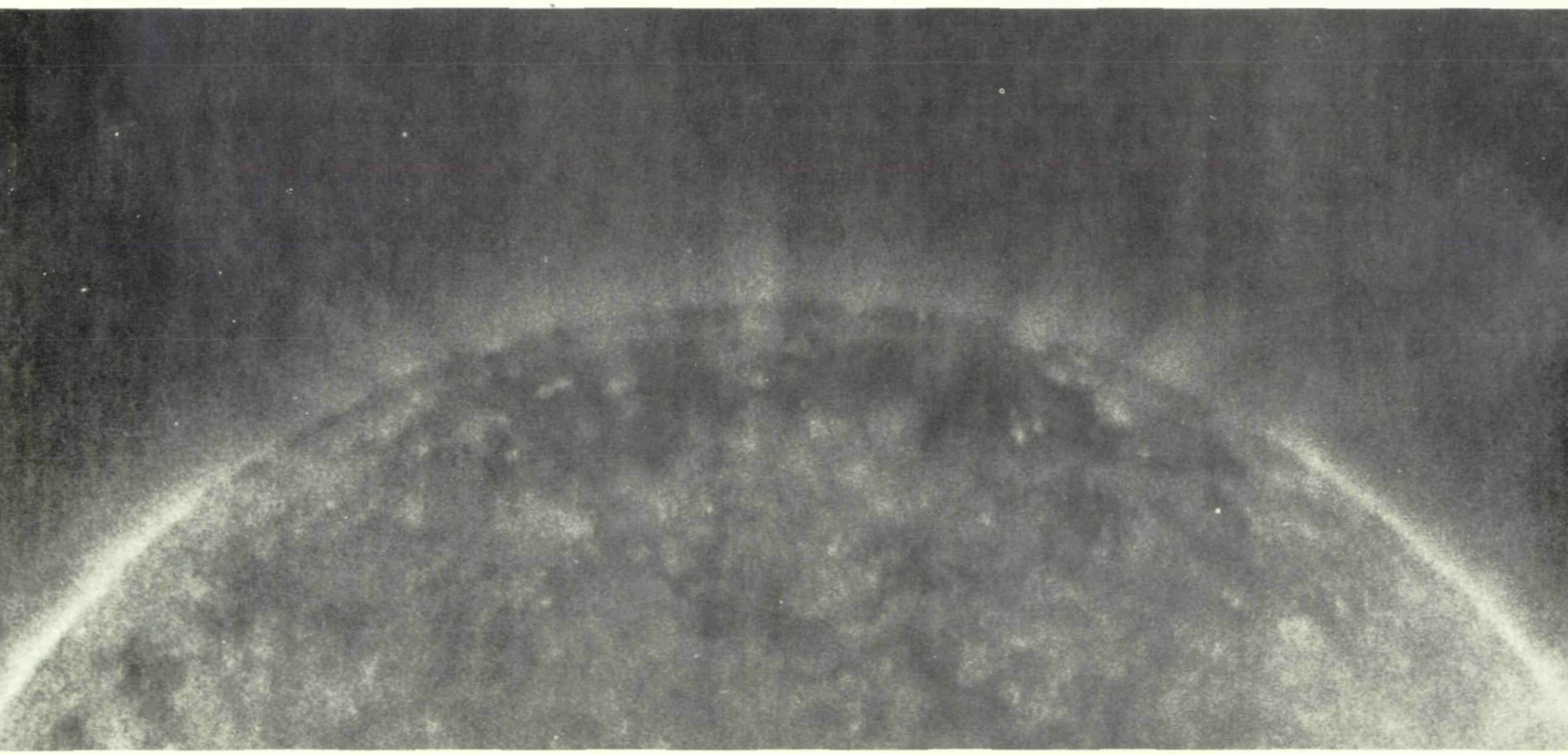
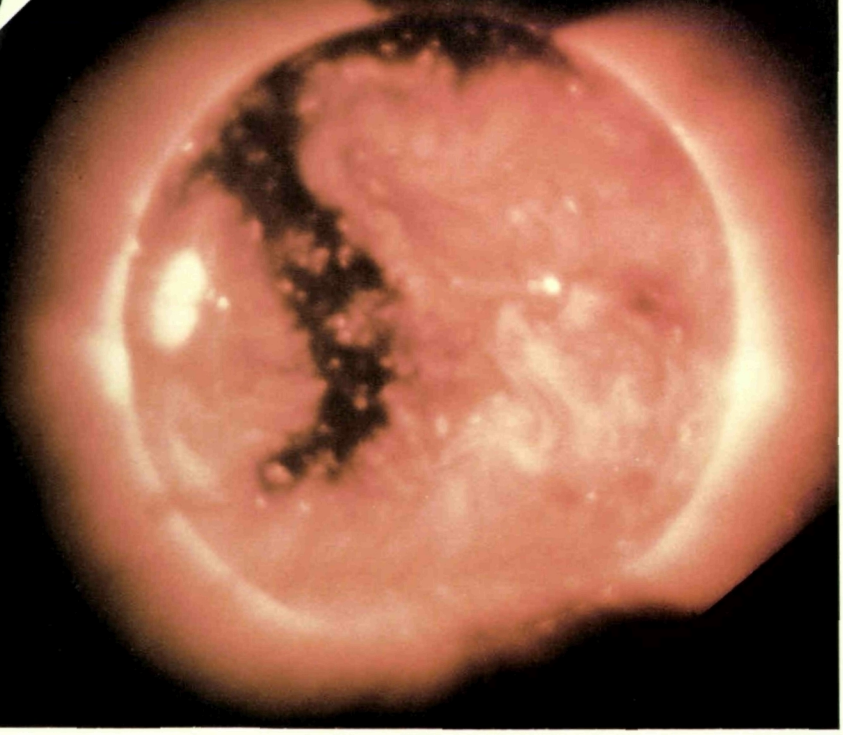
CORONAL HOLES were enduring features at both poles of the Sun throughout the 9 months of Skylab observations. An ultraviolet panorama of the north pole (2) paints a colored picture of a polar coronal hole. Intensity is shown as different colors: brightest is white; darkest, black.

The same area of the Sun seen simultaneously by another Skylab ultraviolet telescope (3) shows the same features at a slightly lower temperature. Polar plumes spring from bright points of emission in the polar hole. At the limb of the Sun the hole is marked by sudden spreading and fading of the bright ring of coronal ultraviolet emission.

3





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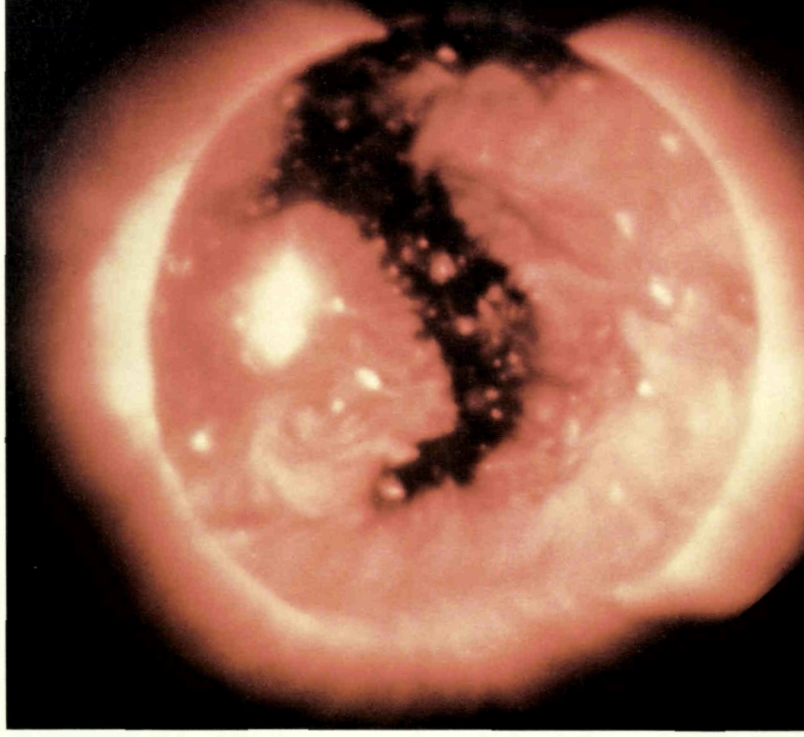

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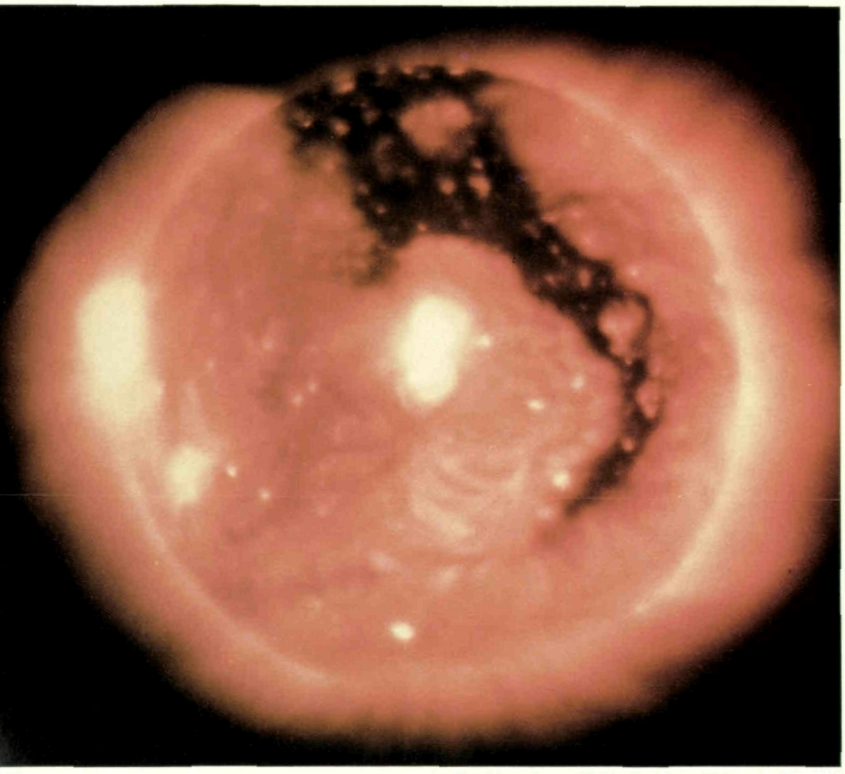

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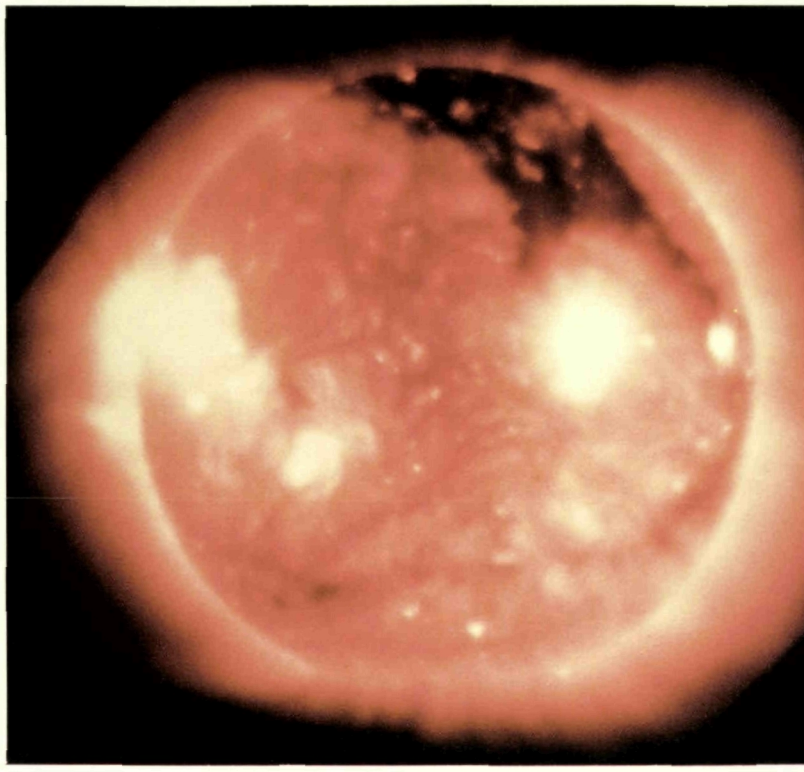
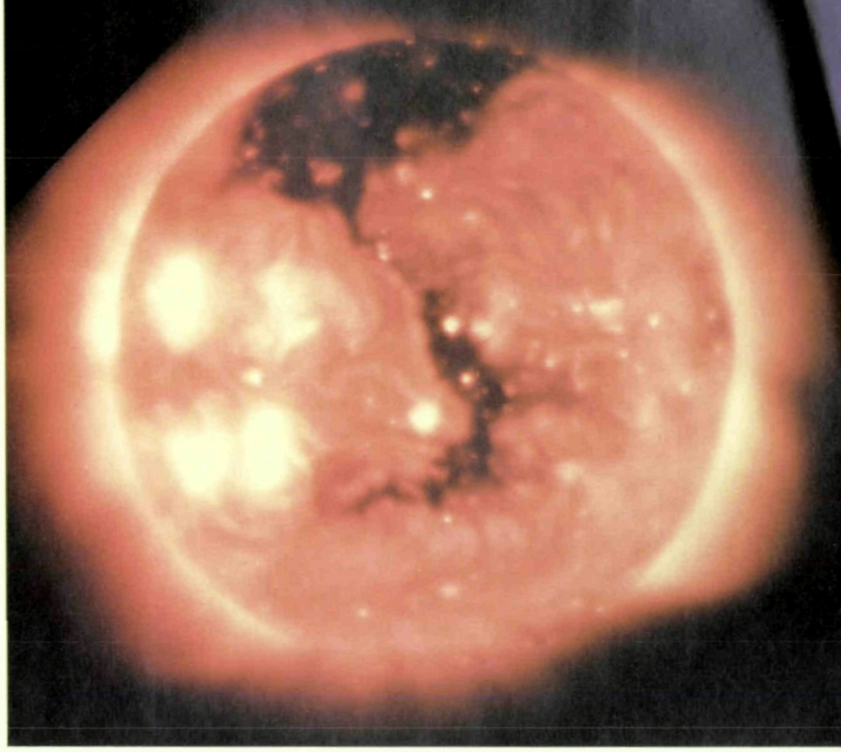


4

THE BOOT-SHAPED CORONAL HOLE rotates with the Sun in a sequence (1-4) of soft X-ray pictures taken about 2 days apart. Most of the apparent changes in this 6-day period result from changing perspective. Skylab data helped demonstrate that coronal holes are sources of high-velocity streams in the solar wind—electrons, protons, and atomic nuclei—that spray out from the Sun into interplanetary space. When the coronal hole is near the center of the Sun, as in (2), the sprinkler is directed at Earth. These high-speed streams of solar wind distort Earth's magnetic field and disturb our upper atmosphere.



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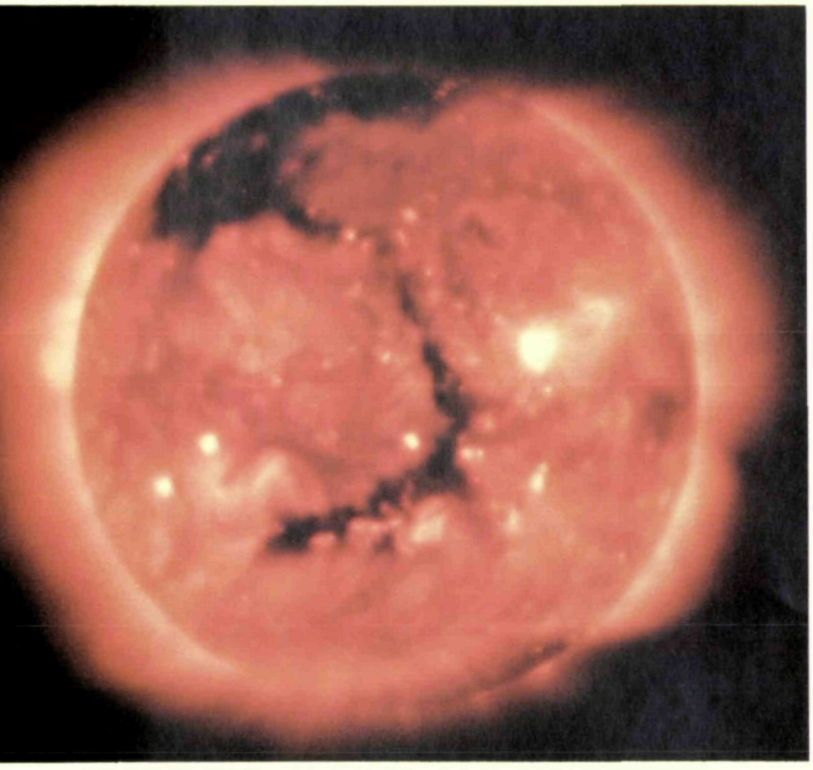

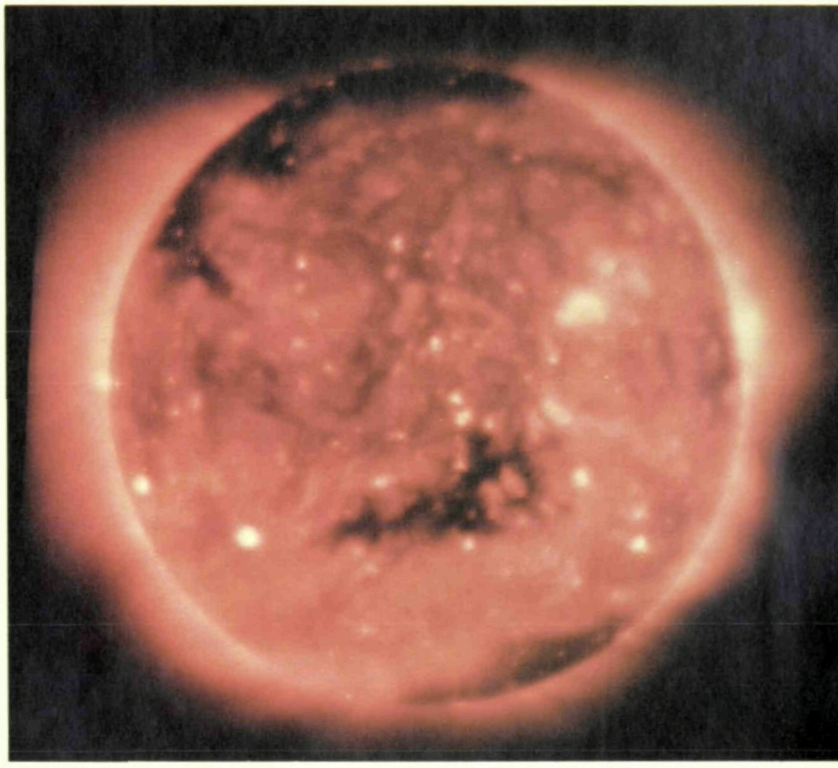

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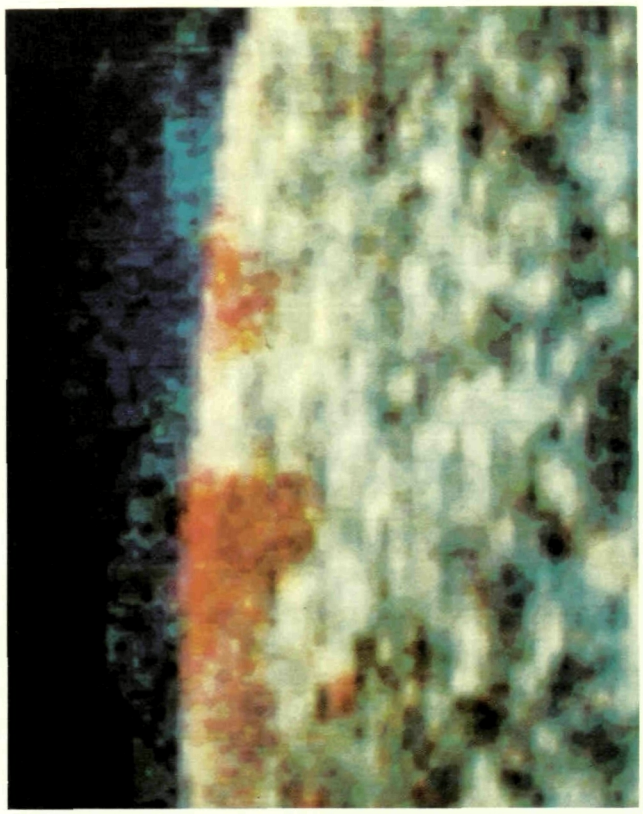
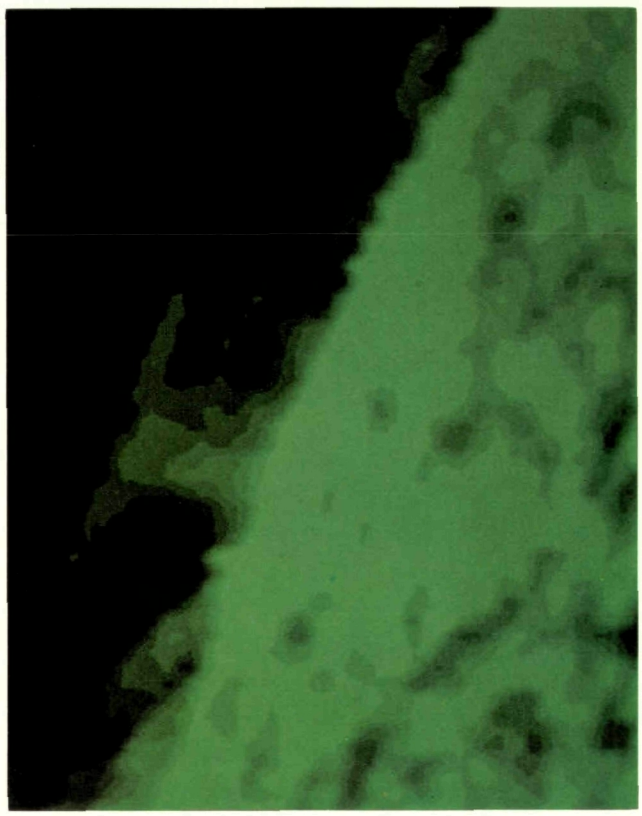
EVOLUTION OF A CORONAL HOLE in about 3 months' time is shown in soft X-ray pictures (5-8) taken at spacings of one solar rotation—about 27 days apart. Neighboring coronal arches encroach like crabgrass into the hole, slowly closing it, leaving only the persistent hole at the north pole of the Sun. Curiously, coronal holes rotate as though attached to a solid Sun, unlike the slipping layers of the photosphere and chromosphere, which rotate much faster at the equator than at the poles.

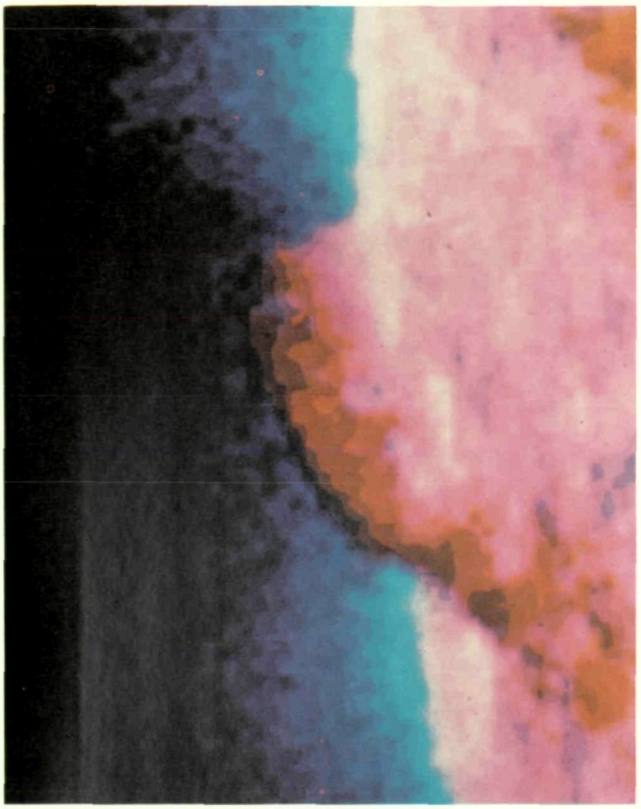
SOLAR PROMINENCES: THE RUFFLED SUN

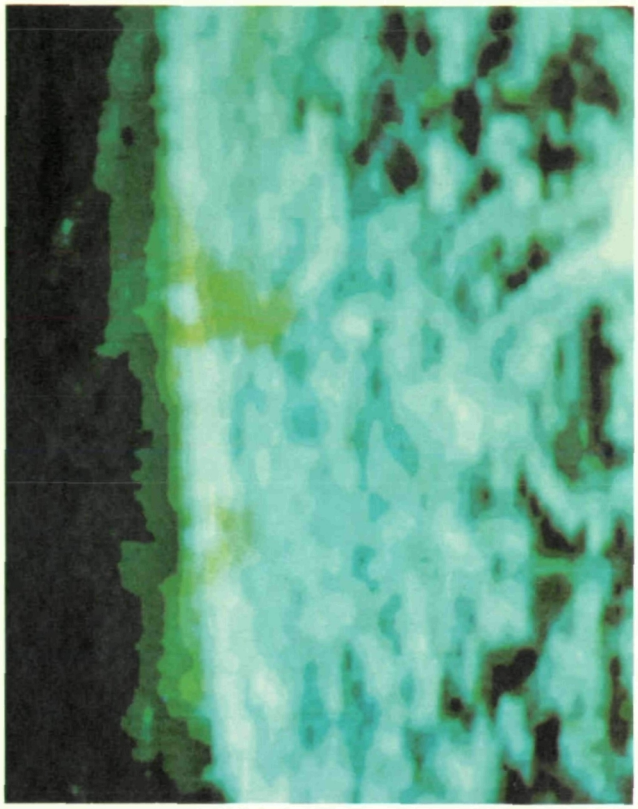
Solar prominences are cloudlike extensions of the chromosphere into the hot corona. Towering to heights of 100 000 km or more, like giant solar altocumulus, they have long been studied as one of the more intriguing features of the Sun. Quiescent prominences are associated with slowly changing solar activity, specifically with large-scale magnetic fields on the surface of the Sun, whose arching lines of force give them shape and support. They appear in varied shapes on the disk of the Sun as long, extended ribbons and persist, in some cases, for weeks or months before fading away. Those that erupt can cause measurable effects in the upper atmosphere of Earth.

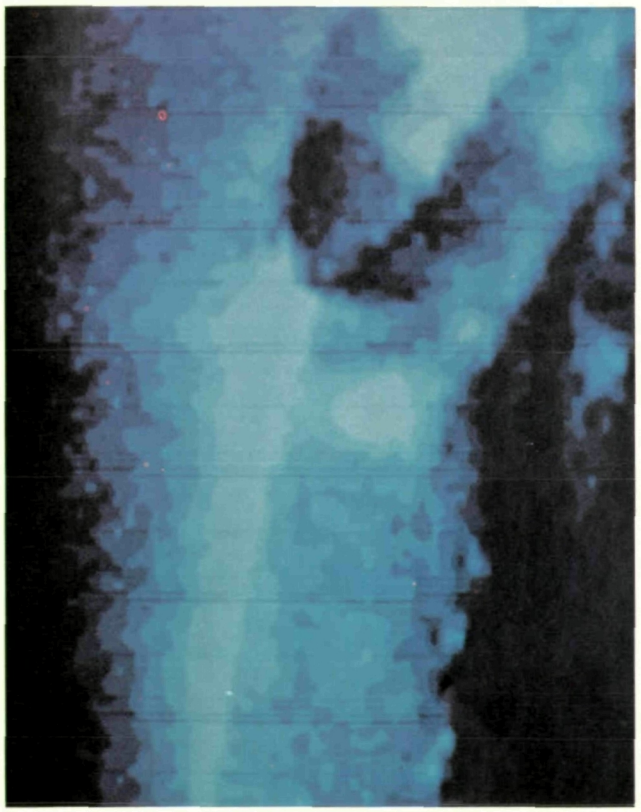
Skylab took these enigmatic features under close observation in the ultraviolet, where, by recording their appearance in different spectral lines and sampling a wide range of temperatures, their hidden structure was dissected, layer by layer. In this revealing process, shown on the following pages, new secrets were ascertained. For the first time, details of their composition were clearly seen: cooler cores, covered by ever larger shells of hotter solar material. In simultaneous pictures, made in different ultraviolet wavelengths, their extension into the corona, carved by refrigerating the hotter coronal atmosphere, could be followed in detail. In the ultraviolet, where hotter, higher shells were seen, their real extent was appreciated for the first time; they were larger than they had ever appeared in visible wavelengths from the ground—immense and delicate ruffles curling above the surface of the Sun.

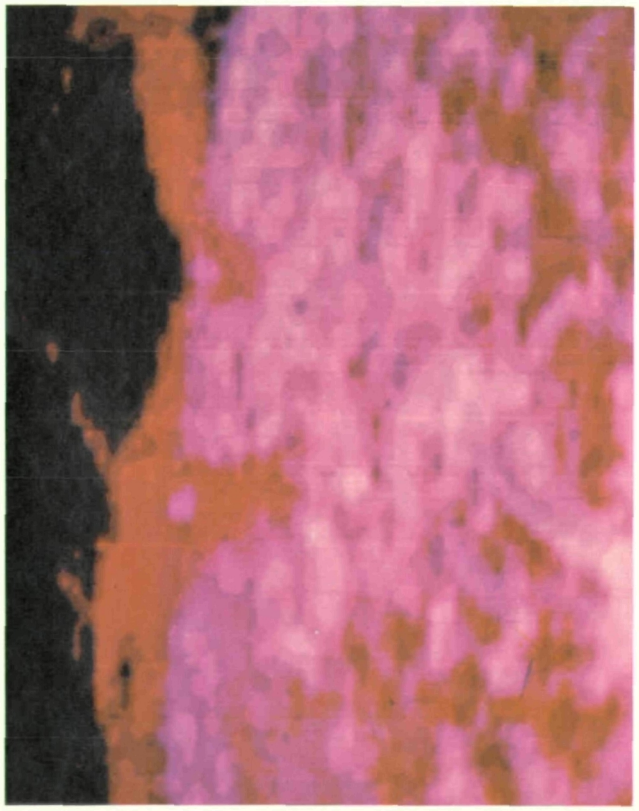


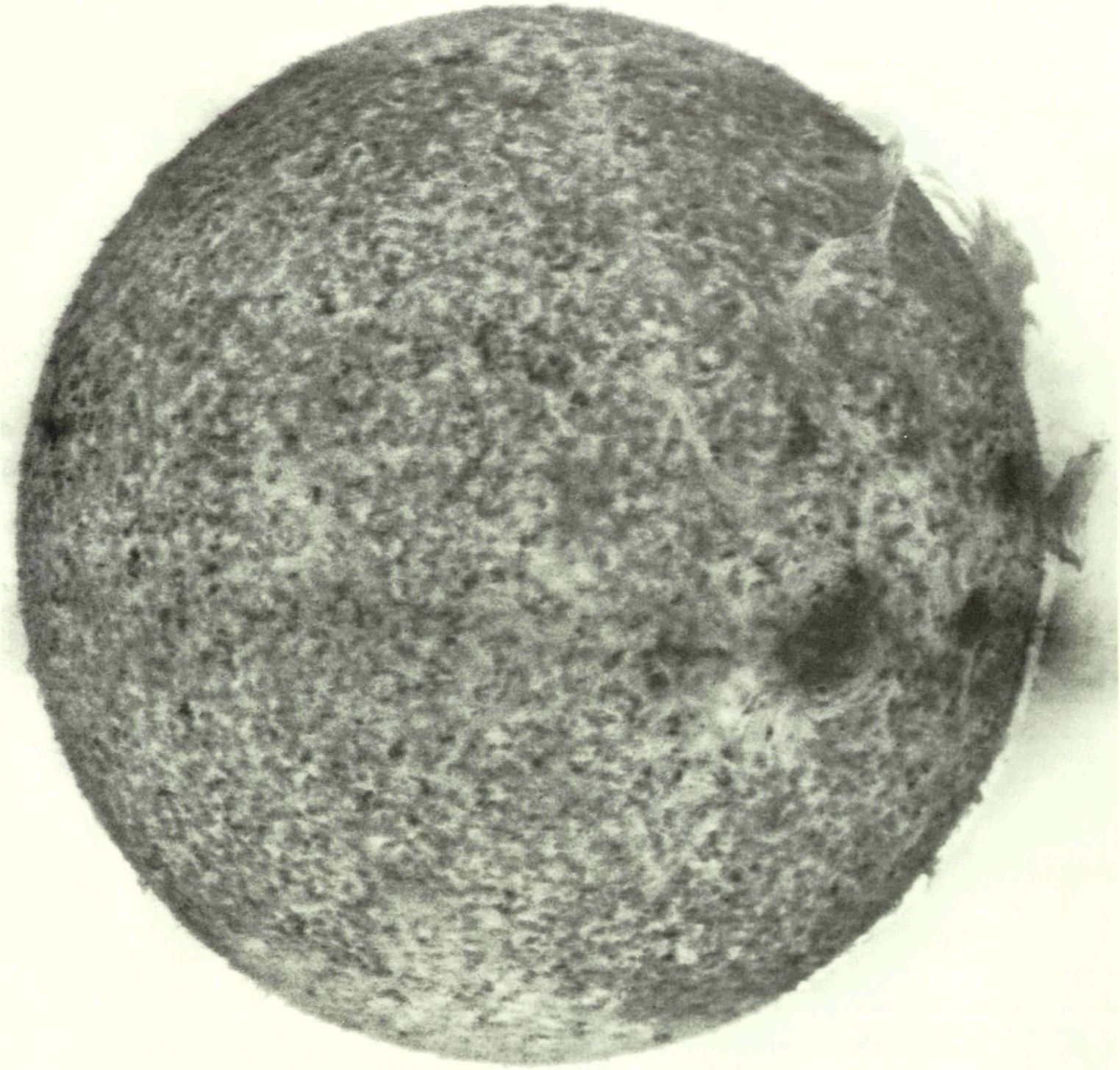




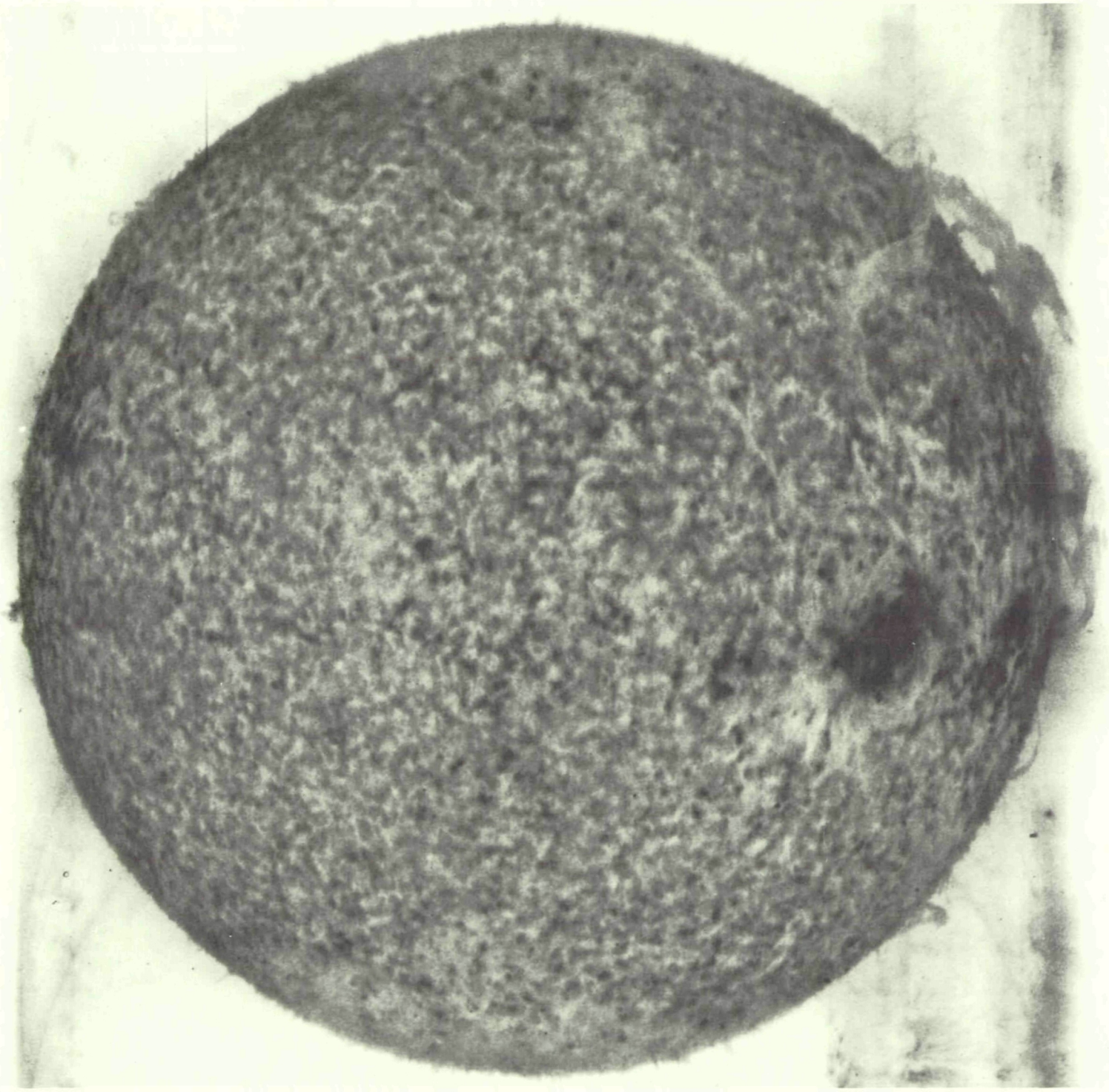




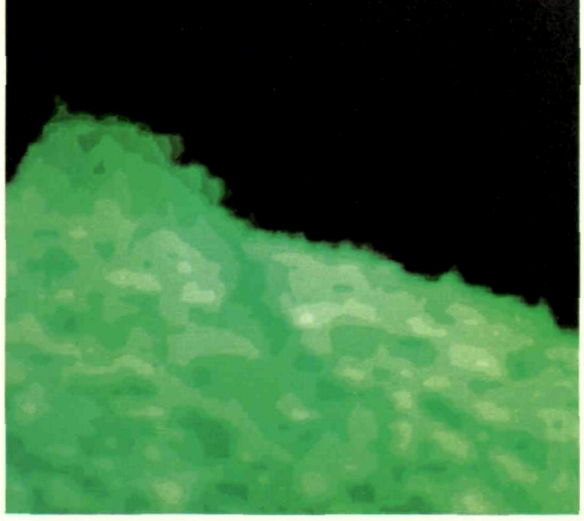




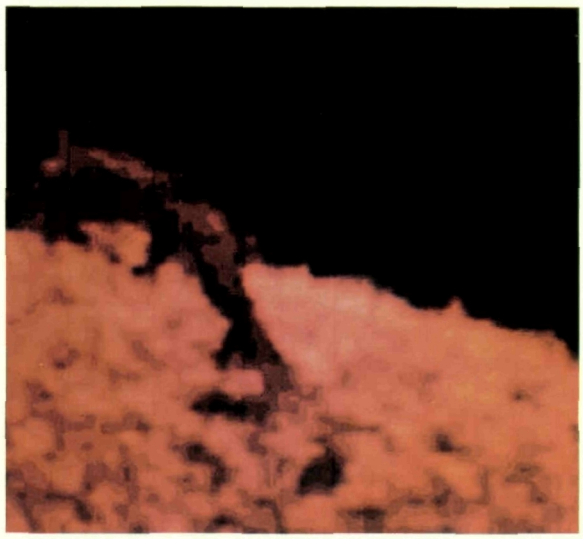
LONG OBSERVED IN H_α as bright clouds above the edge of the Sun, and as dark filaments on the disk, solar prominences take on new, revealing shapes and larger sizes when seen in Skylab's pictures made in ultraviolet light of ionized helium. In solar portraits made 1 day apart, two large prominences curl around the Sun's right limb. The upper of the two can be seen both as a prominence at the limb and as a filament on the disk. Ultraviolet prominences are significantly larger than the same features seen in visible light because ultraviolet emission traces out their hotter, higher reaches. As the upper prominence rotates to the right with the Sun, we see it as a flat ribbon that twists and turns to



form a ruffle around the Sun. Its sinuous form traces out a neutral sheet that separates large areas of opposite magnetic polarity on the surface of the Sun. Prominences last days, weeks, and even months, gradually changing shape, evaporating, and reappearing. Some suddenly erupt as did this large ribbon after solar rotation carried it around to the opposite limb of the Sun 18 days later. Here it floats serenely, suspended nearly 100 000 km above the edge of the Sun, as tall as a stack of seven Earths, and stretching like a giant wall of China nearly one-quarter of the way around the Sun.



1



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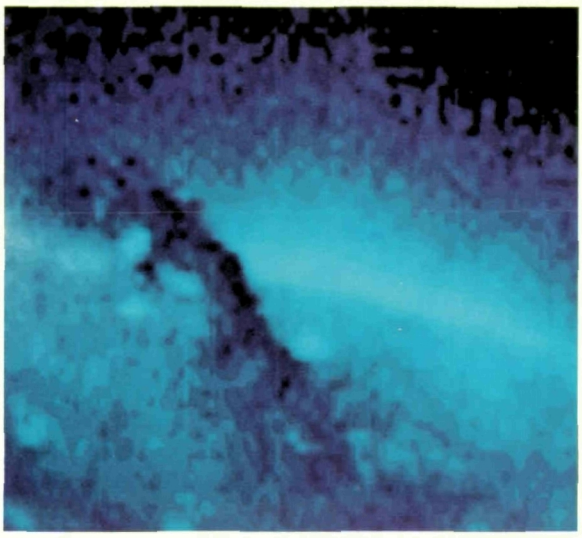

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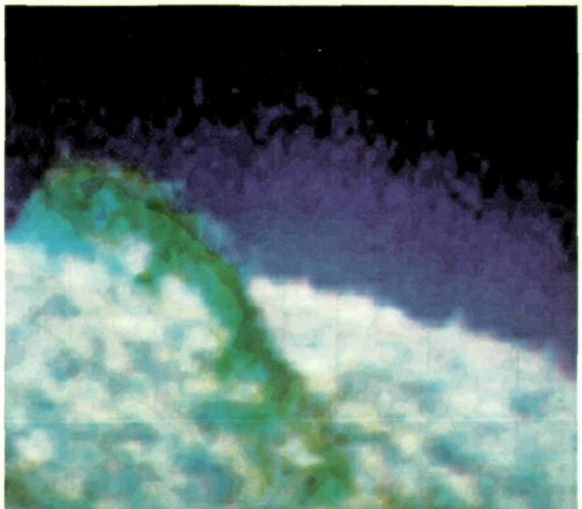


SKYLAB DISSECTS a large quiescent prominence that winds its way around the solar limb. Ultraviolet pictures made simultaneously in different wavelengths (1-3) isolate light from distinct temperature layers. Layers are tagged with different colors in data reduction and are recombined in (4).

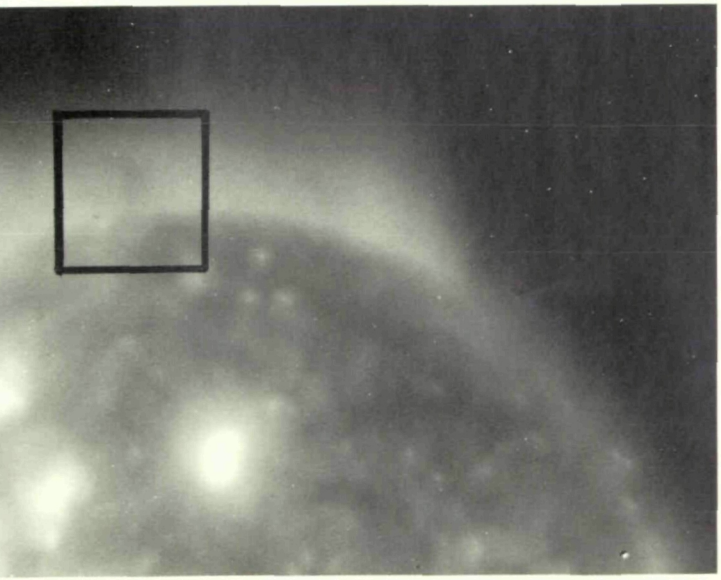
At chromospheric temperatures of about 20 000 K (1), the prominence is barely discernible against the green background. This indicates that prominence and chromosphere are at about the same temperature.

At temperatures of 150 000 K (2), the lower parts of the prominence show up dark against the hotter transition region, demonstrating that they are cooler, denser features.

In coronal light (temperatures of about 1.4×10^6 K), the prominence is a complete shadow (3). Were it not dense enough to block the background coronal light, it would be completely invisible.

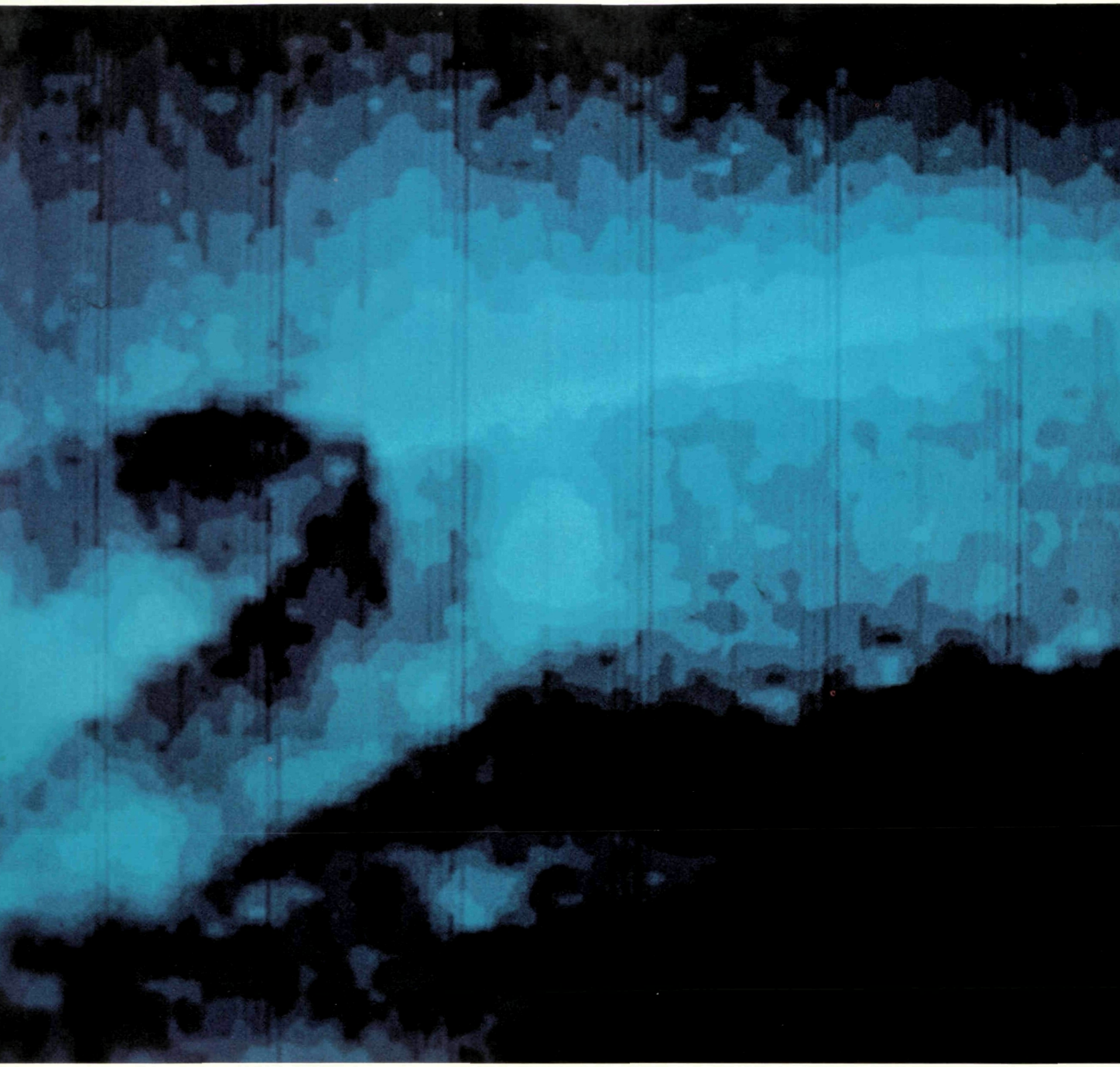
In the composite view (4), white represents the added contributions from all three temperature layers; where one dominates, it appears in its distinctive color. Where the prominence curls over the solar horizon, the blue coronal light is notched away.

5



6

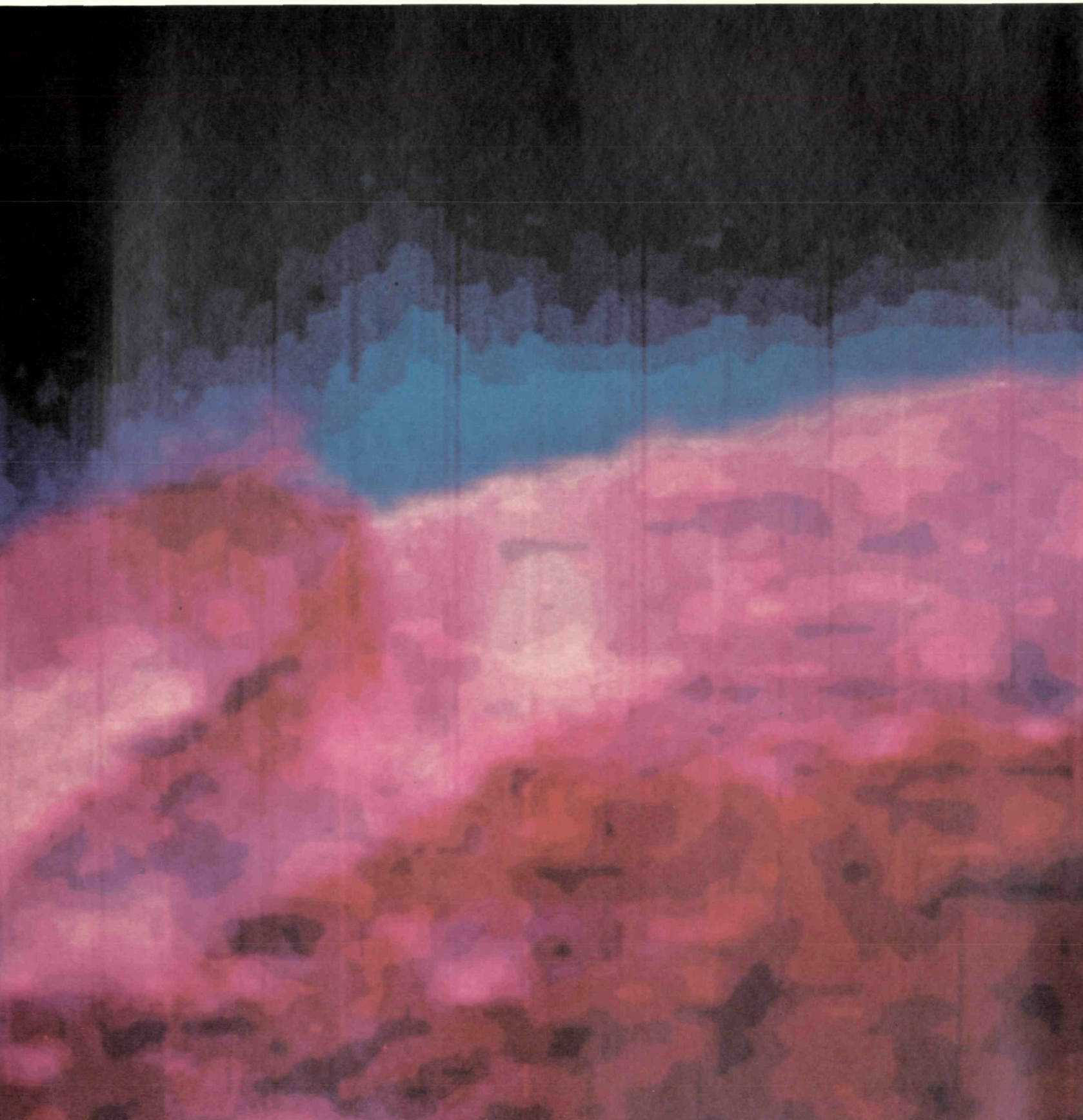
NICKNAMED "PUFF, THE MAGIC DRAGON," the same prominence, big enough to swallow 30 Earths, is seen, crawling over the limb of the Sun, earlier in the day, devouring the blue corona as it goes (5). In fact, the prominence is attached to the chromosphere and moves chiefly with the rotation of the Sun. In the color-coded composite of three ultraviolet pictures (5), red samples chromospheric temperatures, blue coronal, and green the intermediate temperatures of the transition region. Cool and dense, prominences refrigerate the hot corona around them, carving cavities that belie their presence. In a corresponding soft X-ray picture of the corona (6), we see the notch that Puff has made.

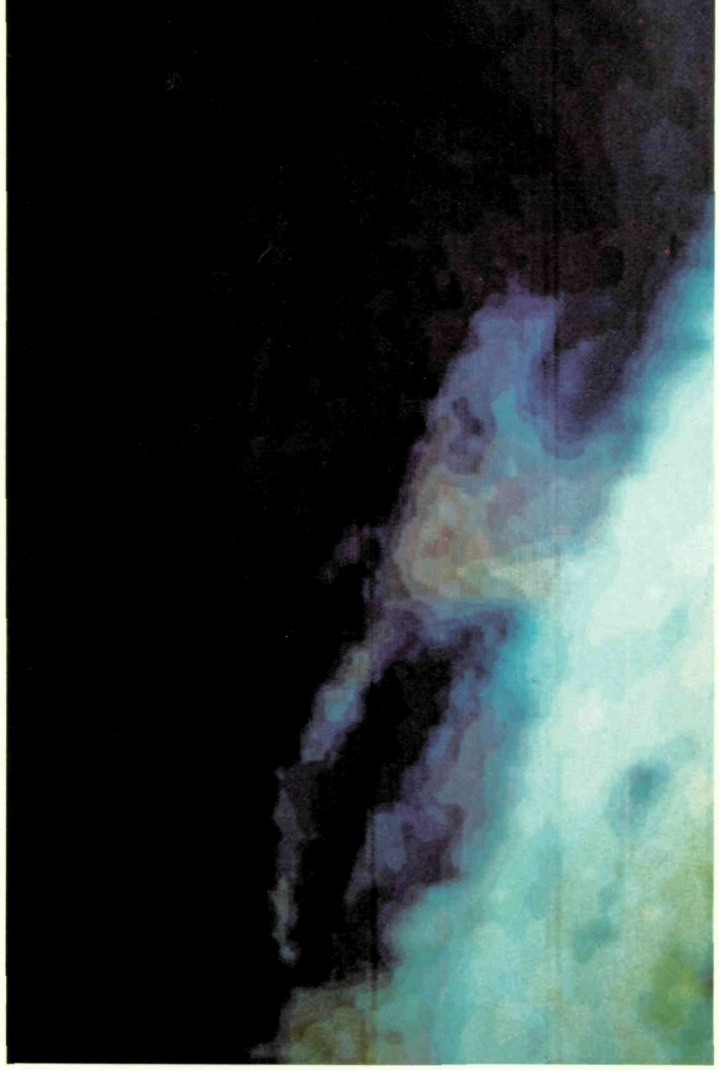


1

(1) CURVING PROMINENCE CAVITY AND NEARBY CORONAL HOLE both appear as dark shadows in a blue-coded picture made in ultraviolet light from the hot corona. The sprawling coronal hole at lower right represents a nearly empty void in the corona, where open magnetic field lines allow the gaseous coronal material to escape the Sun. The curved cavity at left was excavated by refrigeration by a quiescent prominence that still lies hidden within it.

(2) THE HIDING, TROUTLIKE PROMINENCE is exposed when the blue coronal view (1) is combined with a red-coded ultraviolet picture that samples cooler chromospheric temperatures. Red also fills in the coronal hole, demonstrating that coronal holes are not conspicuous features in the lower chromosphere.





1

2

IN LESS THAN AN HOUR an anvil-shaped prominence at the limb of the Sun changes markedly. Composite views (1, 2) were made from separate ultraviolet pictures that sample temperatures typical of chromosphere (red), transition region (green), and corona (blue). During the 49 min between (1) and (2), a large arch fills in, revealing that the prominence is a shredded ribbon, threaded by magnetic fields. Between pictures, Skylab streaked halfway around Earth, keeping its solar telescopes pointed carefully at the same small region of the Sun.

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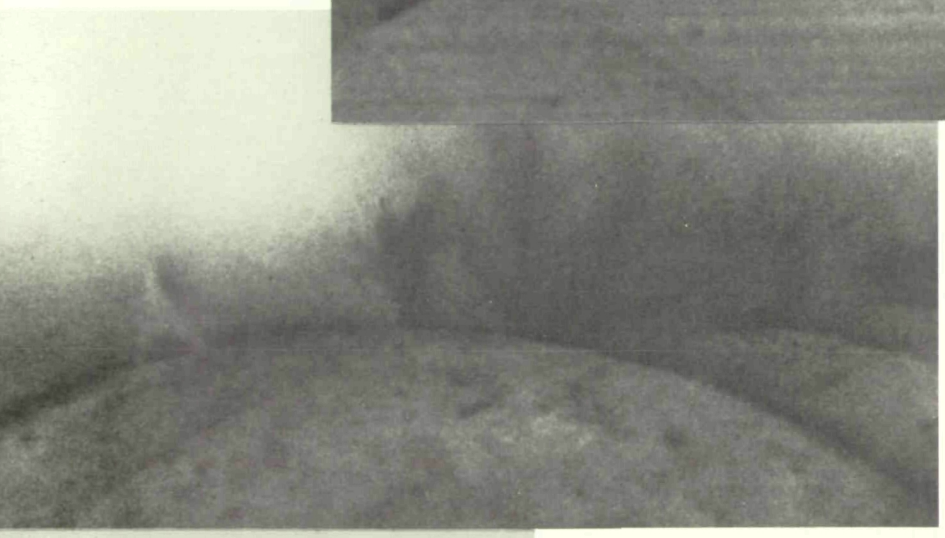
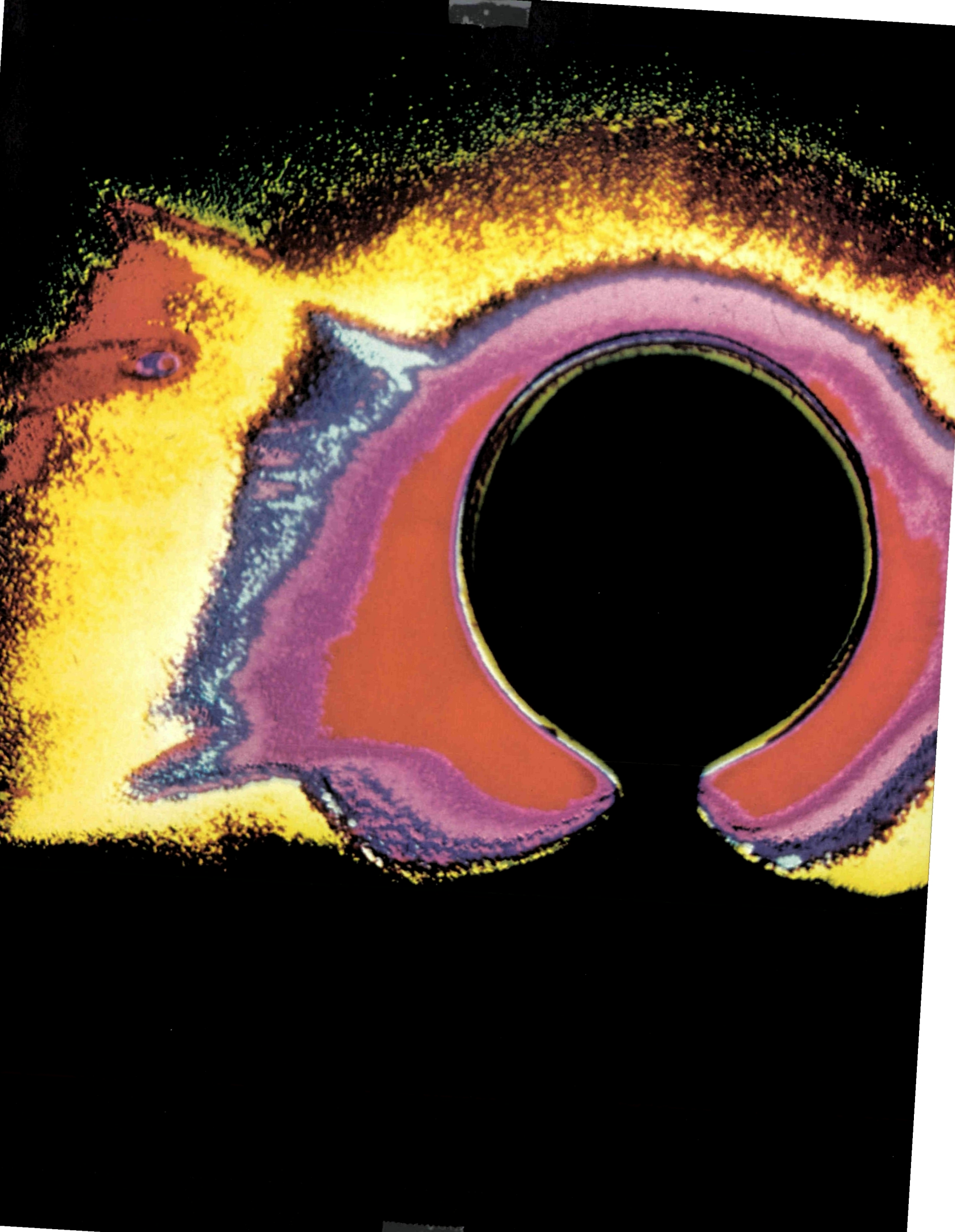
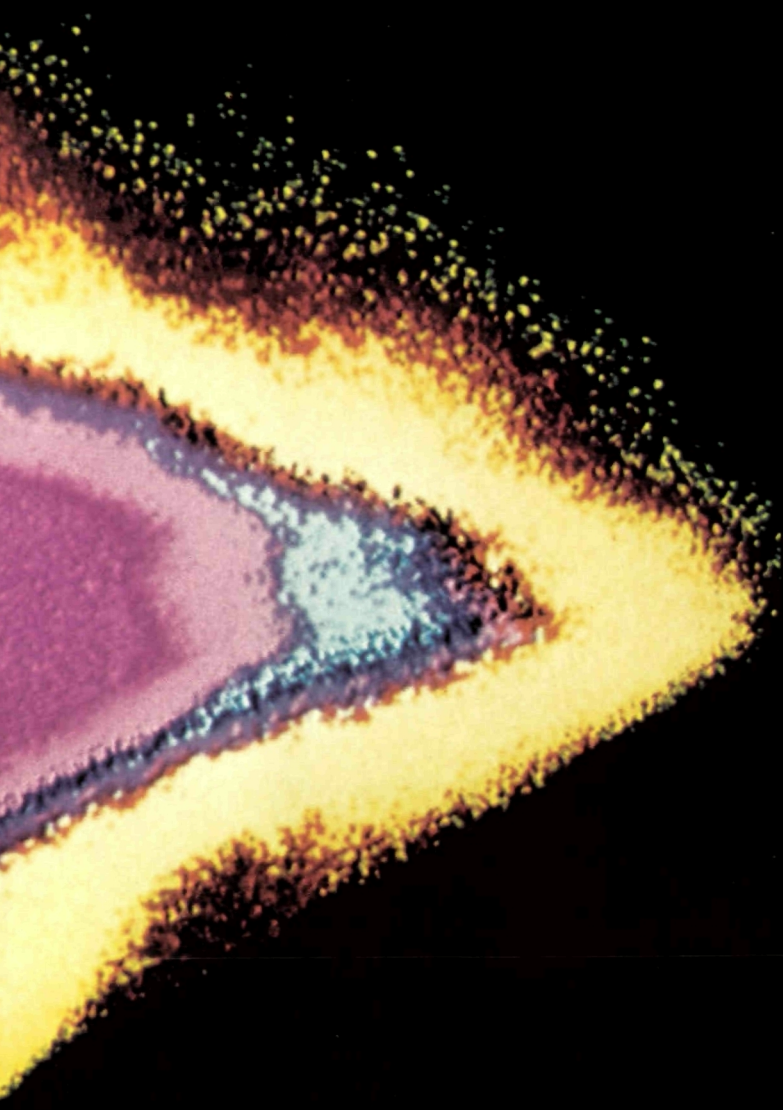


QUIESCENT PROMINENCE AND ADJACENT LOOPS reveal varying structure when dissected into layers of different temperature by ultraviolet pictures (3-7). Such pictures are printed here as negatives so that black means bright. The temperature increases with picture number in these five samples, taken simultaneously. At chromospheric temperatures (3), the prominence is a dense, arched cloud. At higher transition region temperatures (4), most of the prominence fades; nearby loops, filled with material hotter than the prominence, appear in stark outlines. In (5-7), increasingly hot regions of the corona are shown, and the prominence, now a (white) shadow, blocks background coronal light. In the corona both prominence and loops are enshrouded in a foggy haze.



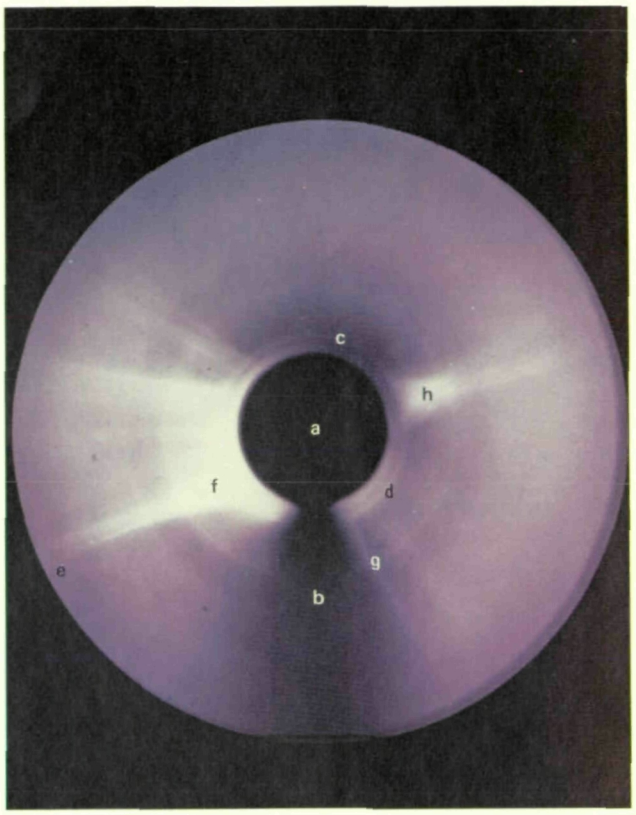


OUTER CORONA: THE ETHEREAL SUN

The Sun's corona stretches far beyond the denser, inner corona seen in X-rays and ultraviolet light, and beyond the limits of what we normally see in the dark sky of a total solar eclipse. Its farthest reaches are delineated by tapered streamers that stretch into interplanetary space, extending the domain of our nearest star much farther than its visible disk. We see the outer corona briefly at total eclipses of the Sun, where it appears white and delicate against the starry background of a temporarily darkened, daytime sky. Even then, Earth's intervening atmosphere is bright enough to limit our view of the outer corona. At Skylab's orbital altitude, where almost no air was left and where the sky was starkly black, the outer corona was at last clearly seen. For 9 months it was continually observed by a coronagraph that blocked out the solar disk.

High on the priorities of Skylab's coronagraph observations were fundamental questions of coronal physics that had long remained unanswered: What are the real shapes of the coronal streamers seen flattened against the sky at times of eclipse? How does the corona change, and in what time scales? Does it respond to the violent changes on the Sun below? How are the inner and outer corona associated with what we feel at the orbit of Earth in the solar wind?

In the thousands of coronal portraits made by Skylab in which the corona was observed more extensively than in all the centuries of man's interest in the Sun, were the expected answers, in clear, continuous pictures of remarkable detail. There were changes of days, weeks, and months. The corona was constantly altering its form, ever adjusting to the shifting forces of the magnetic fields from the surface of the Sun that so obviously gave it its distinctive shape. Like the rest of the Sun, and the rest of the universe, it was never still. Skylab's coronagraph observations coupled with X-ray pictures of the inner corona helped establish the origin of the corona's varied forms and the important connection between coronal holes and high-speed streams in the solar wind.



1

CORONAGRAPH (1) AND X-RAY (2) VIEWS of the outer and inner corona are compared in Skylab pictures taken on the same day. In (3) they are combined in proper scale. Colors were added in printing.

The brightest X-ray features at the limbs of the Sun appear in the outer corona as rays and streamers. These outer features are electrons and protons that have escaped from the lower corona. Their apparent color—white—is simply reflected sunshine. Their paths and concentrations are defined by drawn out open field lines from magnetic areas on the surface of the Sun. More rounded shapes of streamers close to the Sun tell of the last restraining pulls of arched magnetic fields, before the solar particles break away.

(*a*) Occulting disk, 50 percent larger than the image of the Sun

(*b*) Shadow cast in coronagraph by occulting disk support

(*c*) Outer corona is vacant where coronal hole appears in X-ray picture (2)

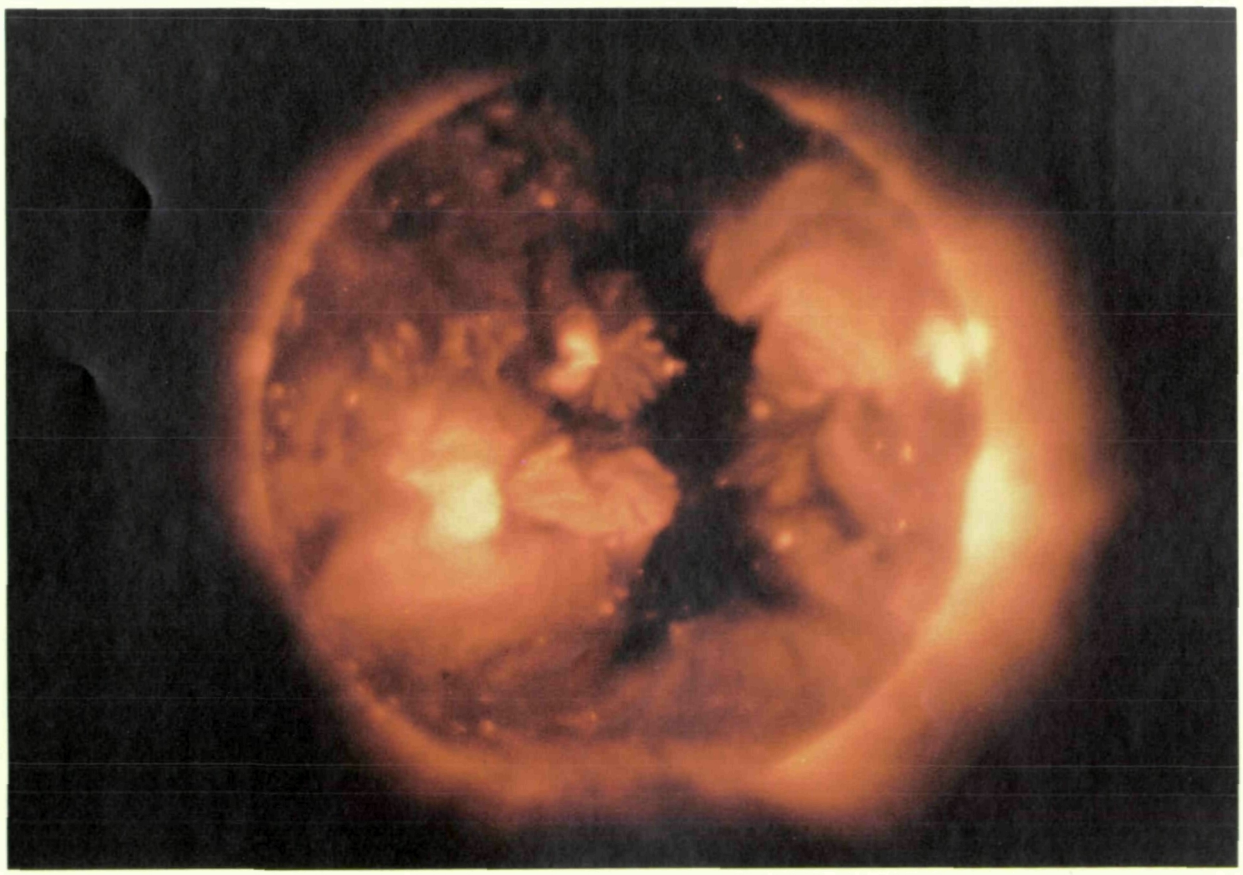
(*d*) Light rings and dark bands, concentric with occulting disk, examples of noncoronal effects of coronagraph optics

(*e*) Outer limit of coronagraph field of view

(*f*) Coronal streamer

(*g*) Coronal ray

(*h*) Coronal streamers, bulb-shaped closer to the Sun



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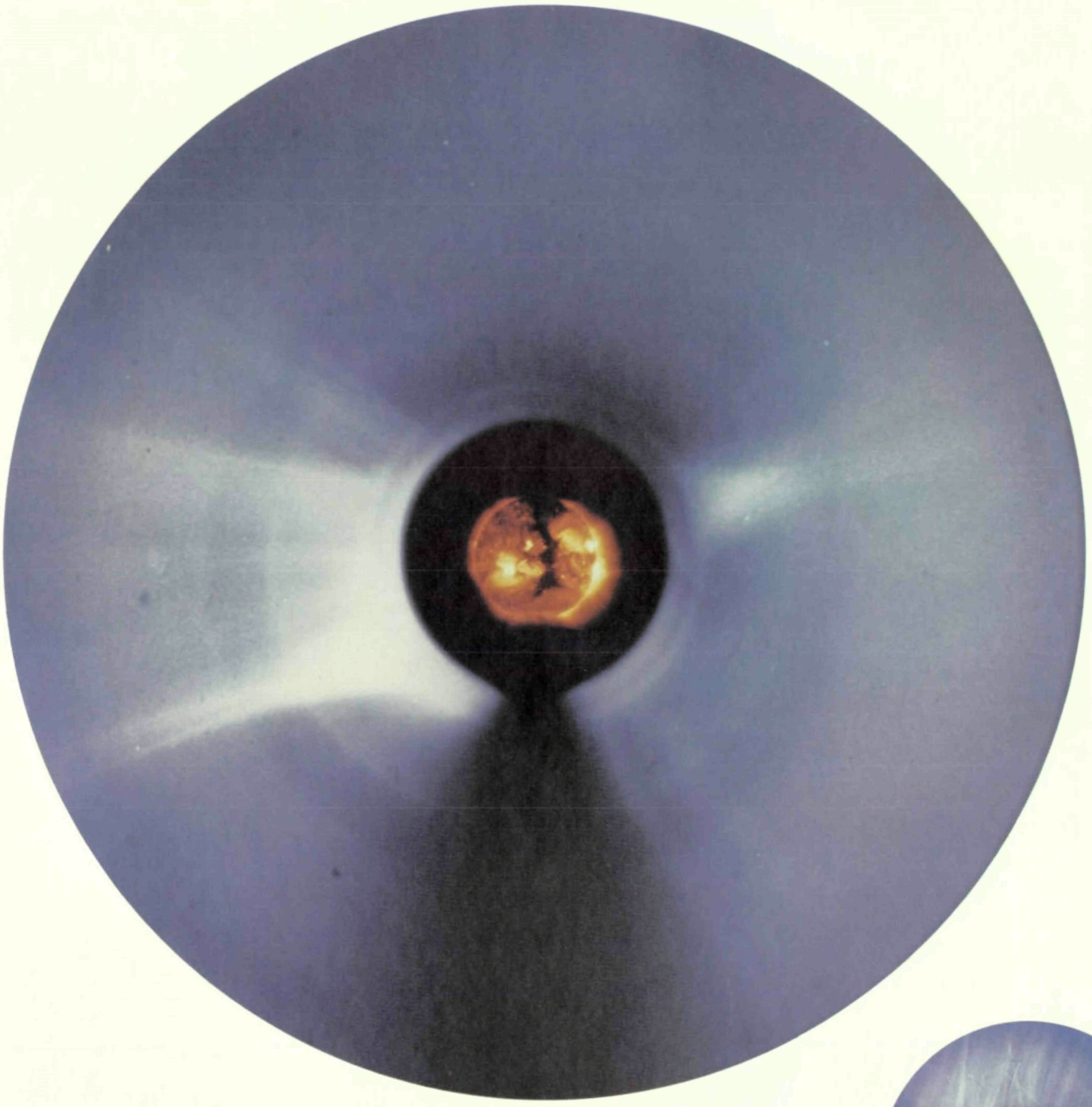

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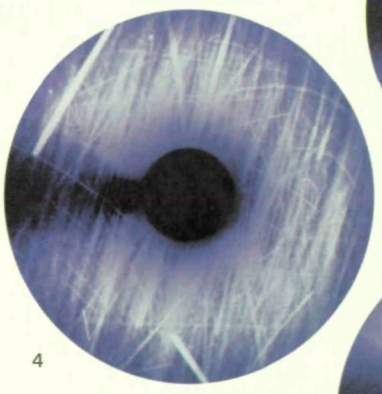

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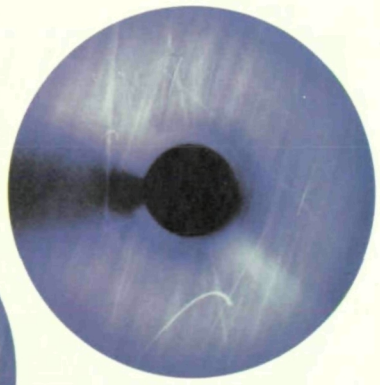

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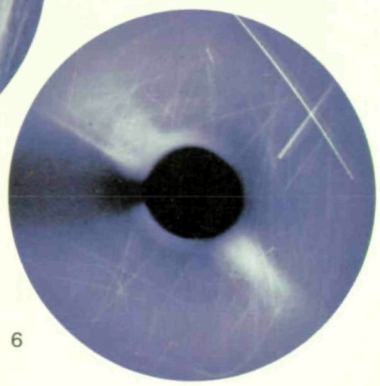
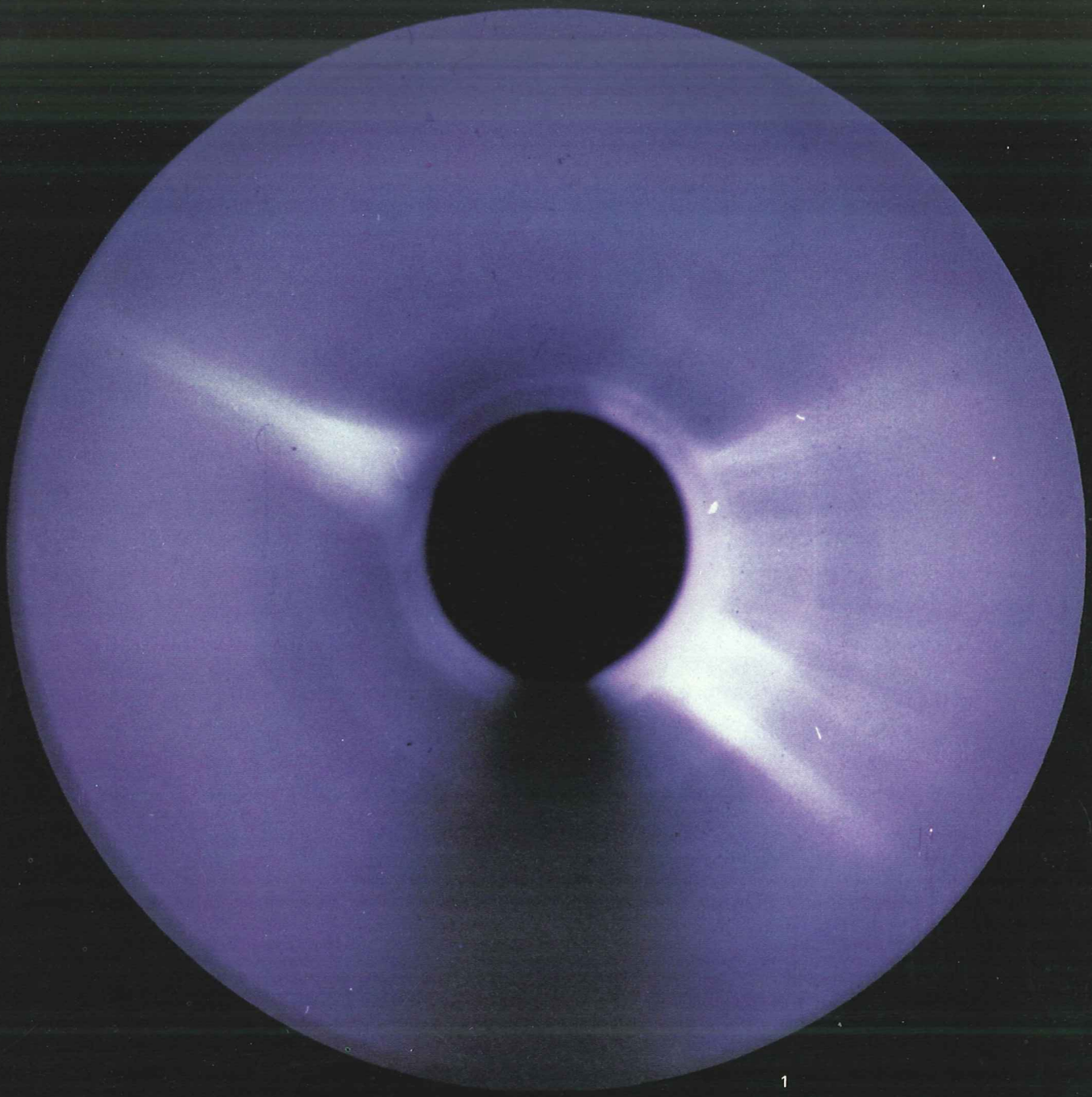


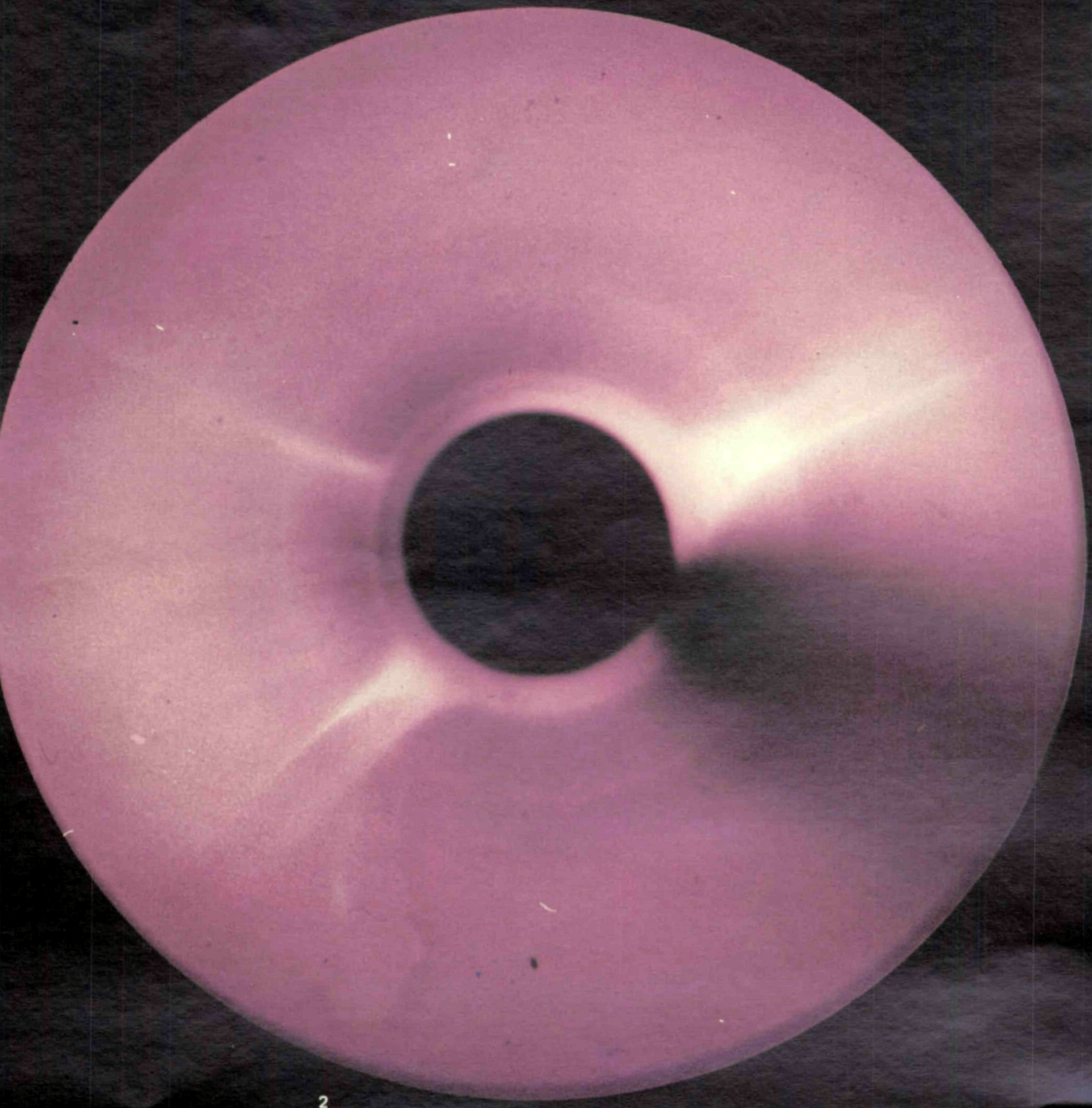
6

ORBITAL "SNOWSTORM" obliterated the corona (4-6) when contamination particles from the spacecraft floated between coronagraph and the Sun. The three pictures were taken within 5 min of each other. Soon afterward, the view cleared. Streaks show the paths of tiny droplets of frozen water that were vented periodically from Skylab's living quarters. Direct sunlight illuminates them like dust motes in a sunbeam, emphasizing the coronagraph's need for an utterly clean sky.



1

MAN'S FIRST DETAILED LOOKS at changes in the outer corona came from Skylab whose coronagraph saw the outer corona flattened in projection against the sky. Long-term changes were apparent as the Sun's rotation carried the corona around, as in a revolving display. Front and back views of the corona are shown in (1) and (2), taken about 14 days apart, during which time the Sun has rotated



2

about one-half turn. The long, pointed streamer at upper left in (1) has swung around in the red view (2) to the opposite side of the Sun; during this time it and other features have altered their appearance. The shadow of the occulting disk support also shifts because of the changing orientation of the spacecraft. Colors were added in printing.

1

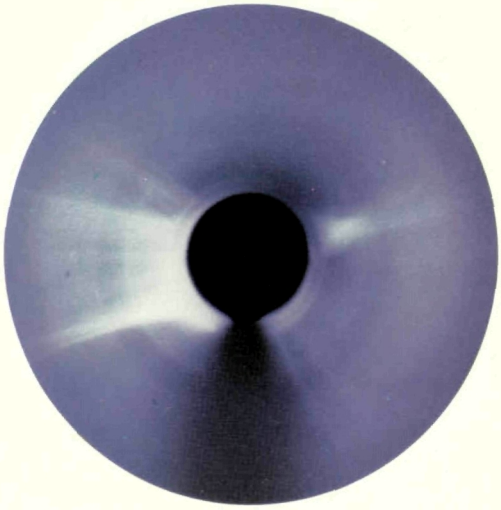
2

3

EVOLUTION OF THE CORONA through one season on Earth appears in views (1-6) taken on Skylab between September 16, 1973, and January 31, 1974. Pictures (left to right) were taken about 27 days or one solar rotation apart, showing the same side of the corona. Coronal streamers sharpen, then diffuse, to be replaced by new structures, responding to changes in the global magnetic structure on the Sun below.

CHANGES IN WEEKS (7-9) are seen below. They are evident in the coronal streamer that extends to the left of the Sun in (7), swings to the right side of the Sun in (8), when the Sun has rotated one-half turn, then appears again at left in (9), altered in shape and direction at the end of one full rotation of the Sun. Pictures (left to right) were taken about 14 days apart.

7



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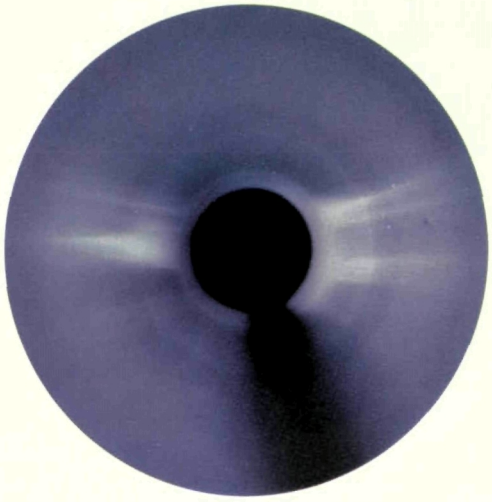

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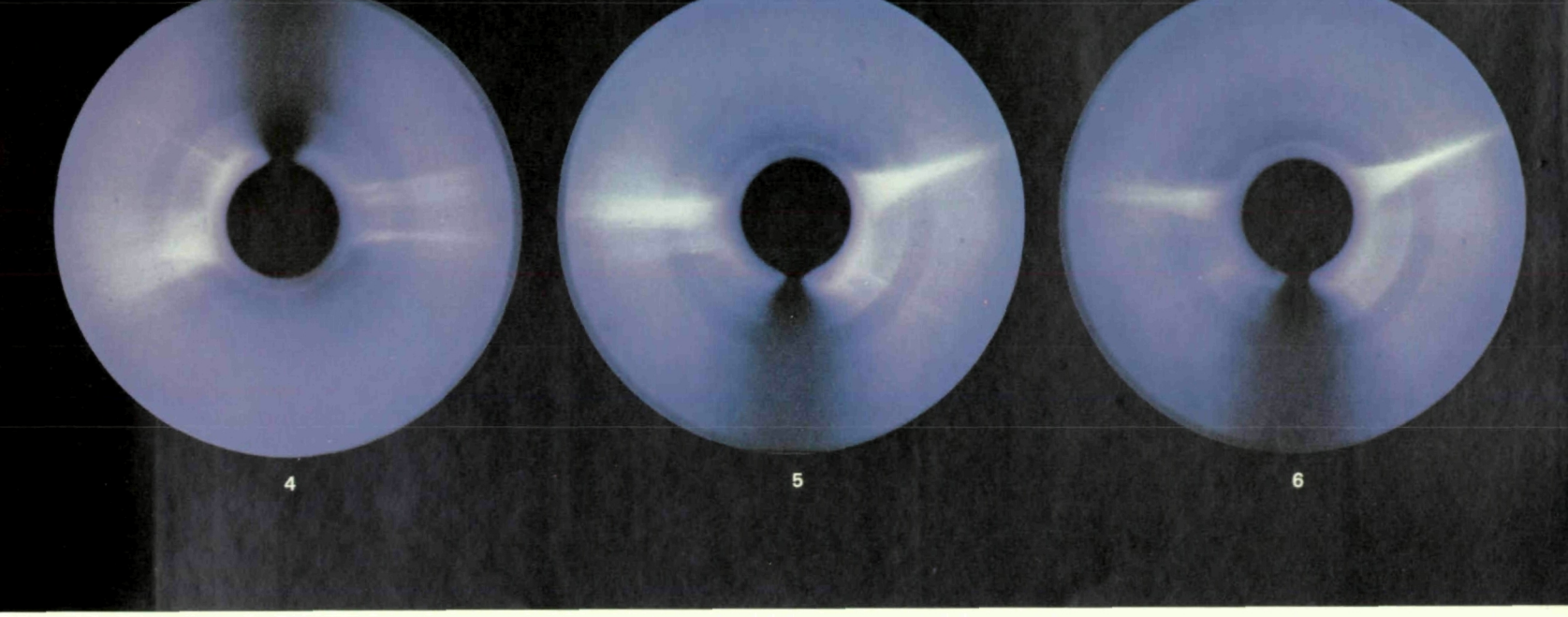
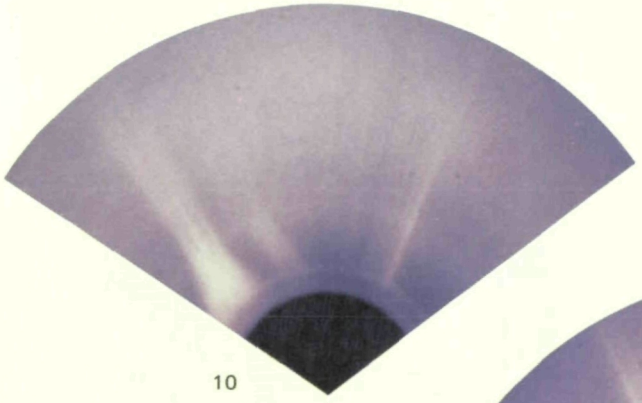
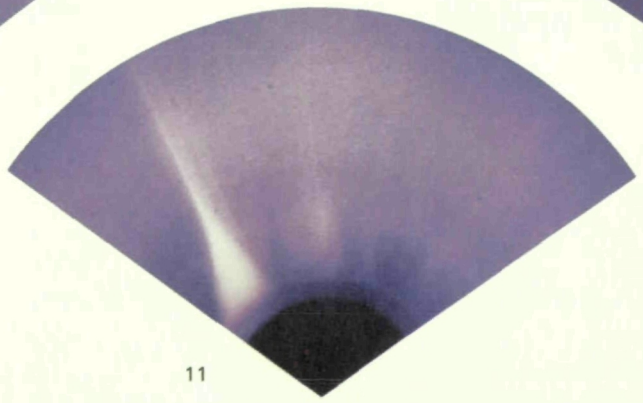
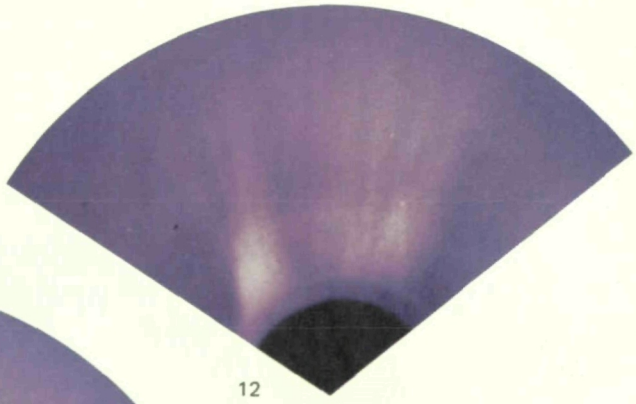
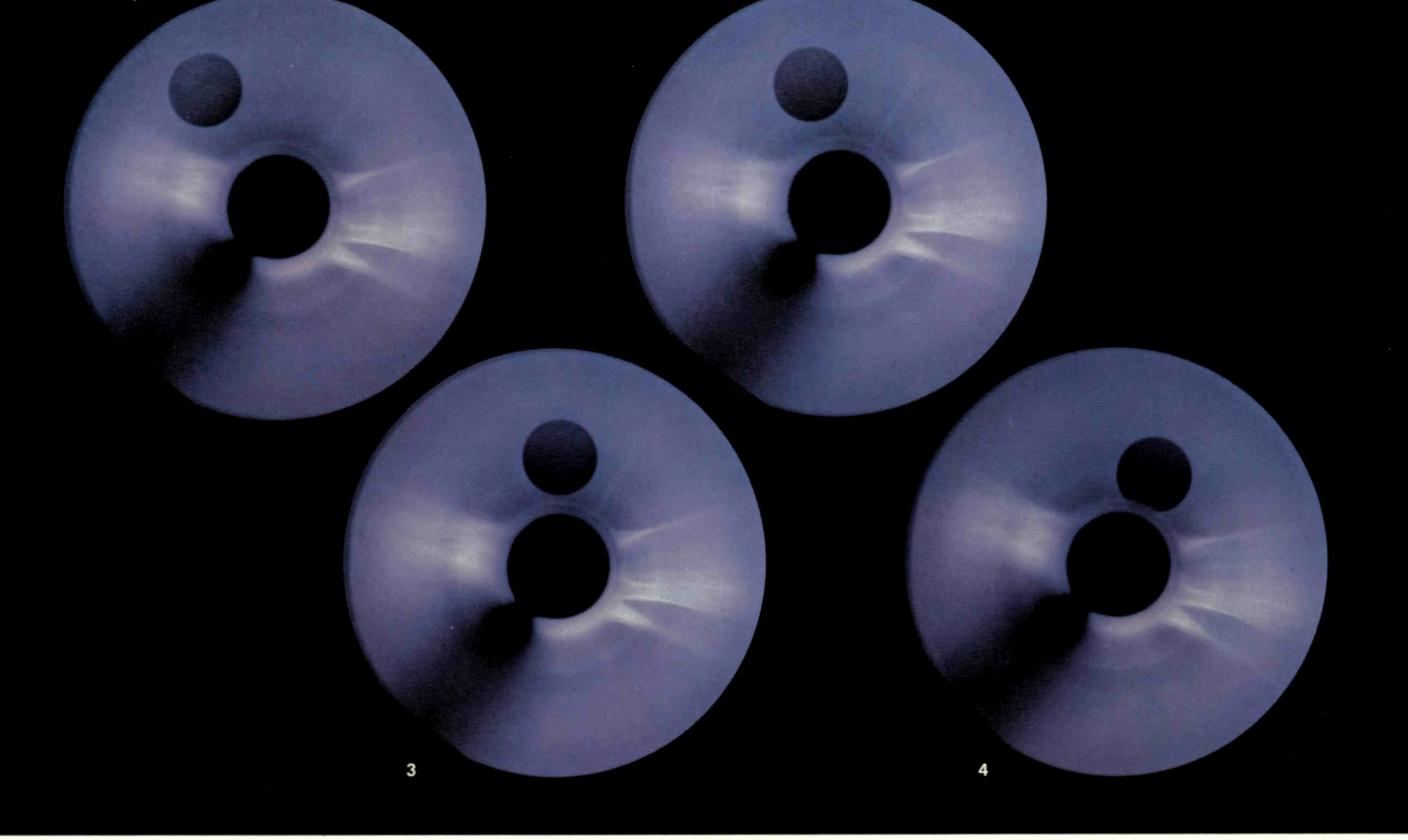


CHANGES WITHIN DAYS in the outer corona are apparent in comparing pictures (10-12) spaced 2 days apart. In this time the right ray vanishes, and the streamer left of it sharpens and then widens again as it swings around toward us. Some of the apparent changes are the result of changing aspects of long-lived features as the Sun rotates them through our view.









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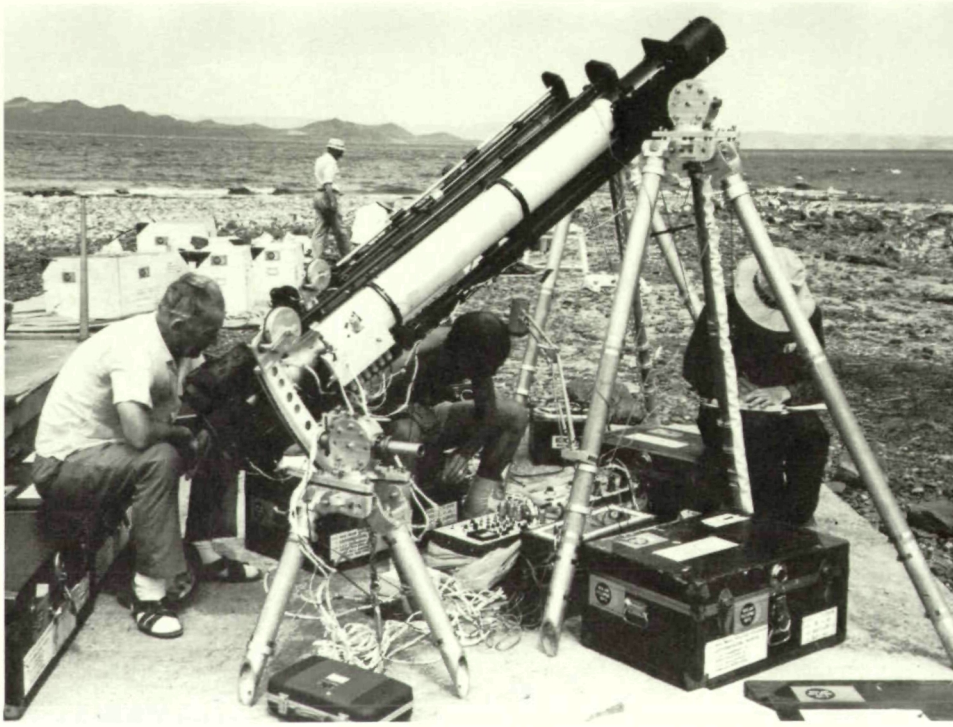
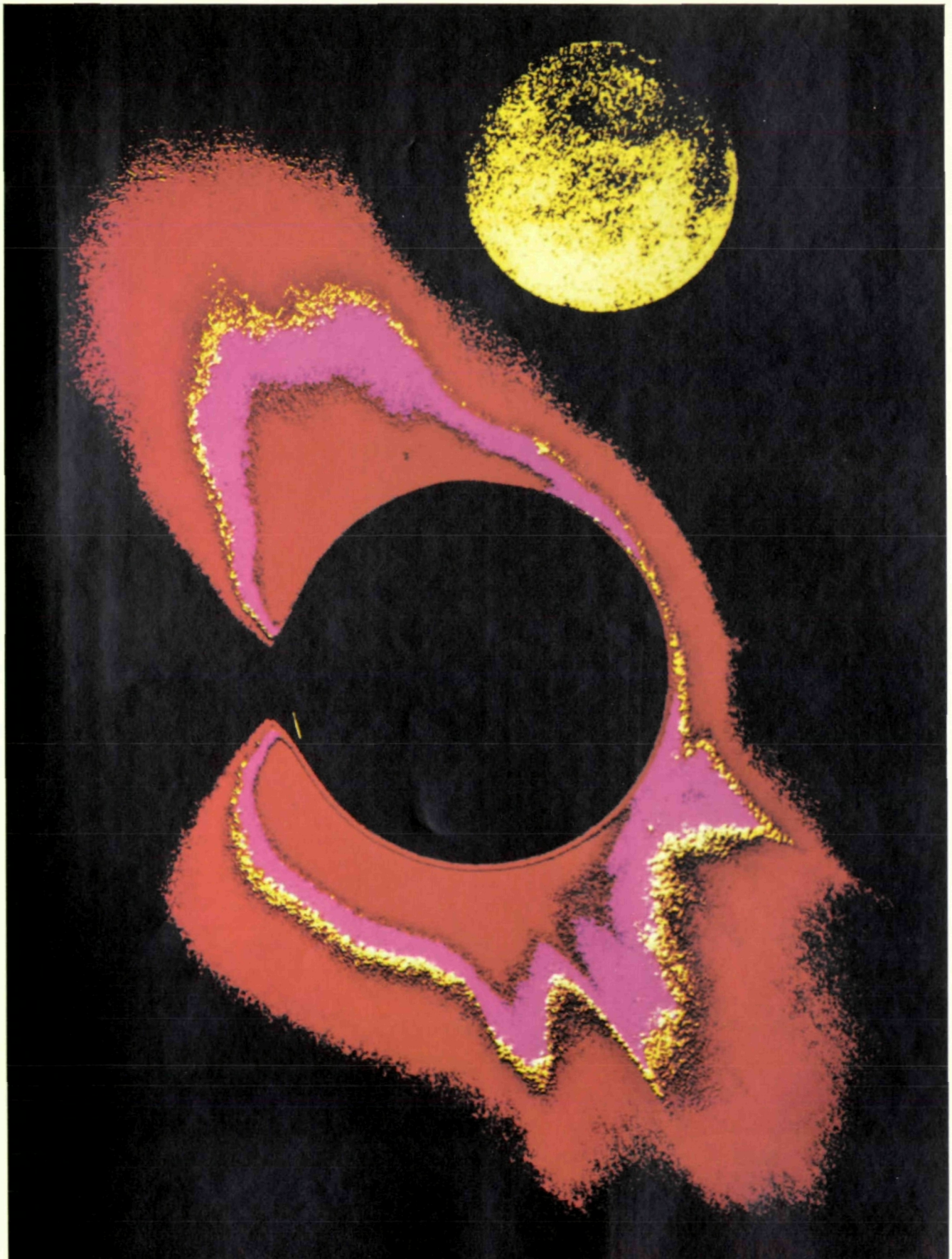
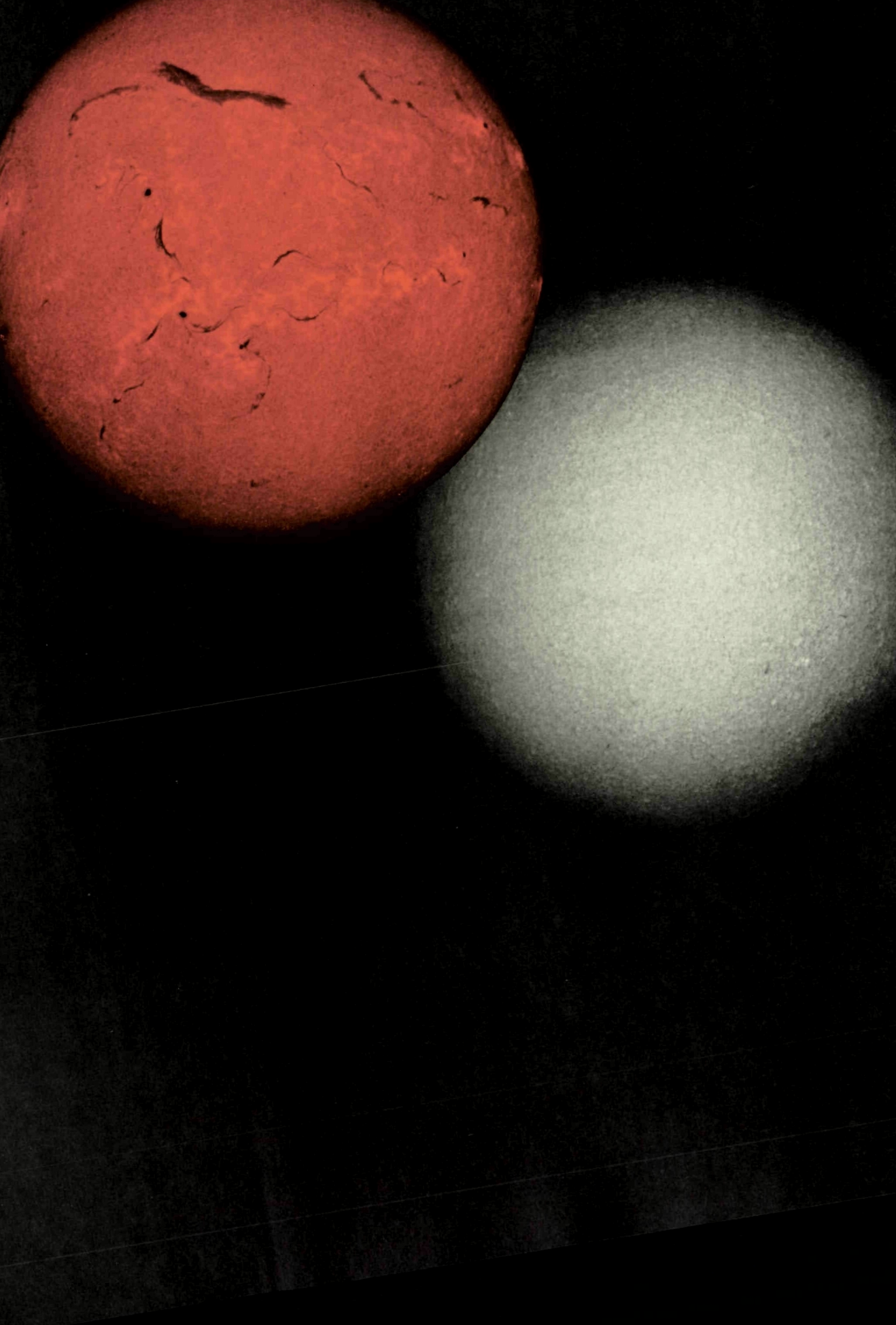


A PSYCHEDELIC ECLIPSE OF THE SUN was created by special photographic processing of black and white coronagraph film from Skylab. A new Moon, here tinted yellow, moves across a flaming pink and red corona. Truth is less exciting: In reality, the Moon is gray and the corona white. Colors added here distinguish subtle differences in brightness.





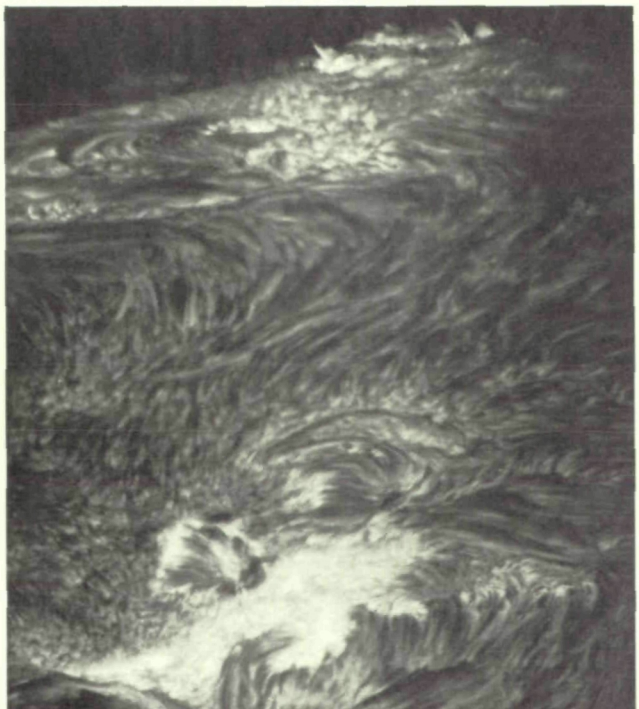
7
The Active Sun

Johnson Space Center (June 15, 1973, 14:09): *Skylab, Houston. Be advised we understand in active region 31 there is a subnormal flare that is now in progress, and two of our instruments are recording information from it.*

Astronaut Joe Kerwin, M.D. (12 minutes later): *Houston, Skylab. I'd like you to be the first to know that the pilot is the proud father of a genuine flare.*

The surface of the Sun, once thought to be smooth and unblemished, has been shown with modern telescopes to be a seething inferno that is never still. Today, with the best modern telescopes, at the best observing sites, and on the best days, we can watch the roaring chromosphere in almost frightening detail, as in the dramatic picture at right from the Sacramento Peak Solar Observatory. But even in these superb, ground-based pictures, we see but a limited part of the real action on our Sun. In the chromosphere, and in the even more unstable layers above it, which are not visible from the ground, a variety of catastrophic events occur: explosions and eruptions on scales unknown on Earth. Skylab observing programs were planned to make the best use of the chance to record these same violent events in X-ray and ultraviolet wavelengths to seek their causes; to trace, for the first time, their full extension through all the layers of the solar atmosphere; and, with the coronagraph, to observe their impact in the outer corona of the Sun. Sunspots were easy targets, but detailed observations of more explosive and shorter lived events required constant vigilance, both in the spacecraft and by the many Skylab support scientists on the ground. When the Sun became more active, an even closer watch was kept. The effort paid off: Skylab observations of action on the Sun were the most fruitful and comprehensive ever made.

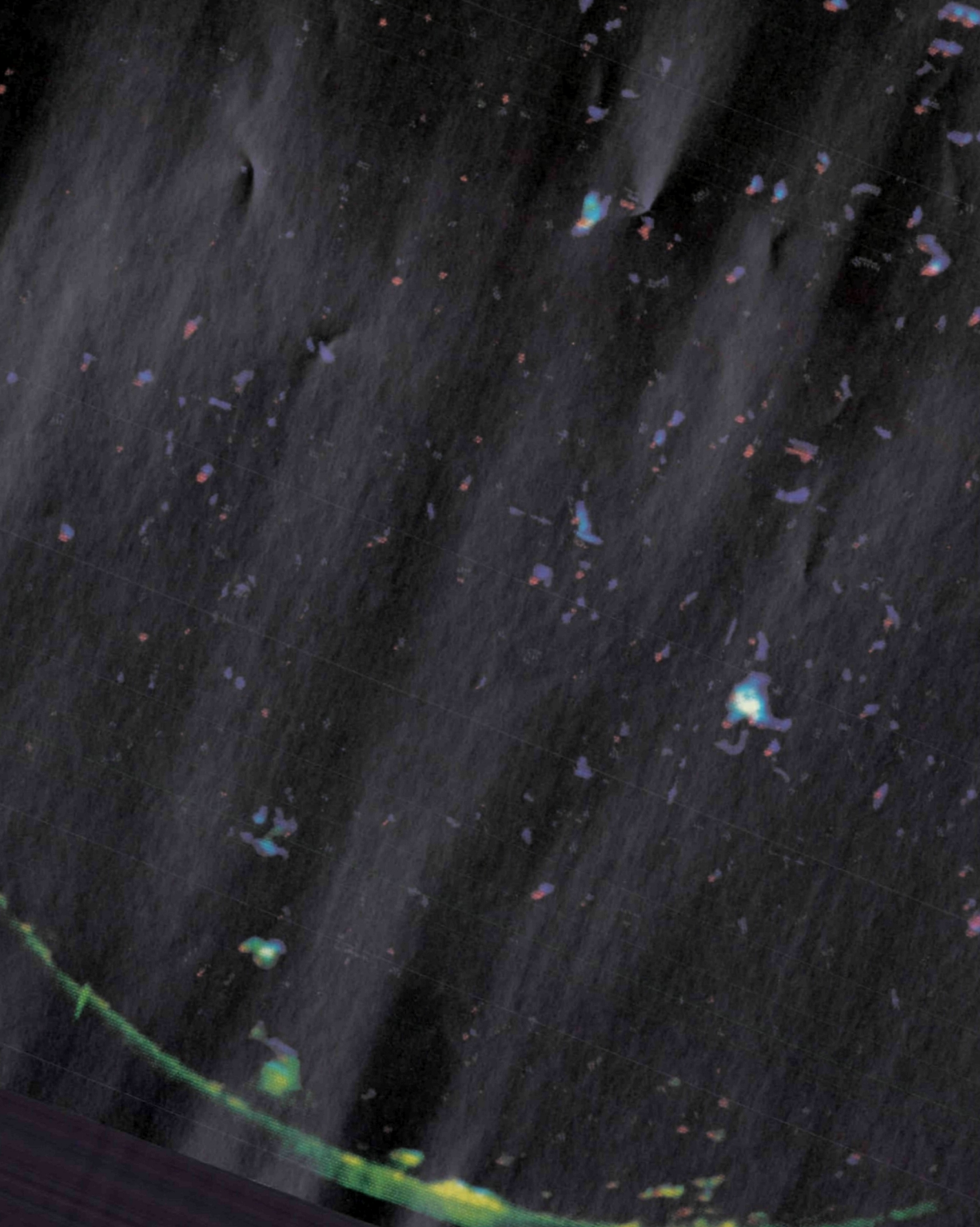
Skylab observations revealed the magnetic nature of active regions on the Sun, how they are woven from looped lines of magnetic force, and how new active regions are born, interconnect, and eventually die. From carefully taken Skylab data in ultraviolet and X-ray wavelengths have come important new insights into the elusive nature of solar flares, their exceedingly high temperatures and confinement—in crucial early stages only seen by Skylab—to tiny and intense loops of magnetic force near the surface of the Sun. Flare precursors, found in real-time X-ray pictures taken by Skylab astronauts, may help in making practical predictions of these terrestrially important solar events. Skylab observations of the active Sun established the fundamental role of another new solar feature of the X-ray and ultraviolet Sun called "bright points." Associated with intense, compact mag-

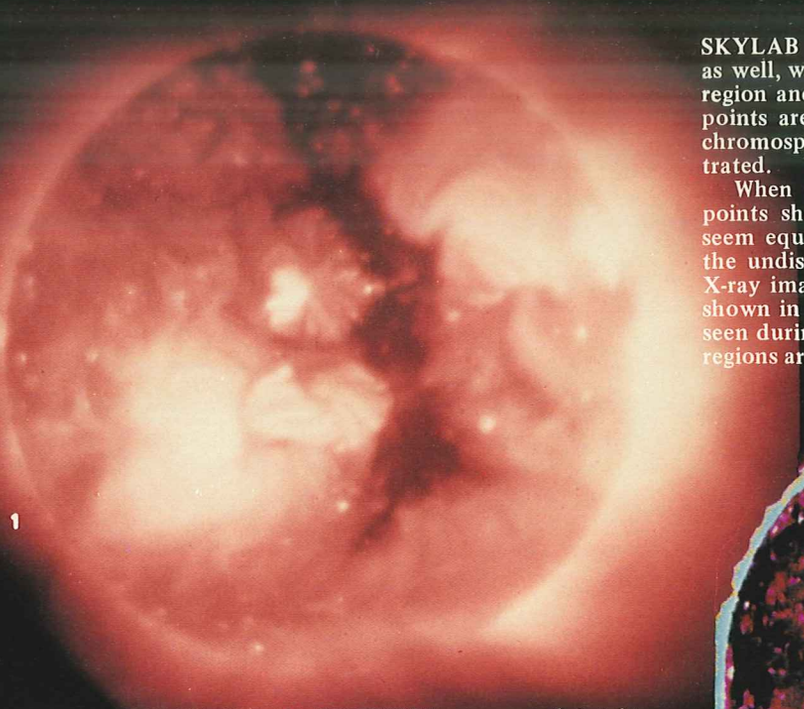


netic regions, bright points account for a major fraction of the magnetic energy on the surface of the Sun. Like sunspots, though of shorter duration, they come and go, but by a surprising set of rules: all over the Sun they increase in numbers and magnetic flux as sunspots and active regions wane, perhaps to balance the overall magnetic budget of the Sun. As such, they add a new dimension to standard pictures of varying solar activity and alter long-held concepts of the nature of cyclic, solar change. Caught in the net of Skylab's coverage of the outer corona were a truly dramatic find—scores of the immense clouds of coronal material called "transients" that are propelled outward from the Sun by the initial force of flares and prominence eruptions. Some expand to exceed the size of the Sun itself and travel outward toward the planets, with recognized terrestrial effects.

BRIGHT POINTS: THE GLITTERING SUN

Solar features called "bright points" are small, pointlike sources of X-ray and ultraviolet emission, like tiny lights glowing in the upper atmosphere of the Sun. They were first observed in earlier rocket images made in X-ray wavelengths, and confirmed and better studied in Skylab's extensive coverage of the Sun. Smaller than sunspots, but also associated with intense, localized magnetic fields of opposite magnetic polarities, they have now been shown to be an unappreciated and basic element of solar activity, perhaps as fundamental as sunspots, which for so long have served as the standard index of change on the Sun. Unlike sunspots and larger active regions, bright points were found in Skylab coverage to extend all over the Sun, even appearing at the poles and in coronal holes. A significant fraction occurred predominantly in active regions in lower solar latitudes, following the usual pattern of activity on the Sun. About 10 percent show explosive brightening, like miniature flares, increasing in brightness by a factor of 10 in about 10 min. Unlike other known classes of solar activity, bright points are of short duration, lasting less than half an hour. Several surprising features of bright points have come from the analysis of the Skylab films. They seem to increase in overall numbers on the Sun as other known signs of activity fall, as though to balance the overall budget of activity on the Sun. Of equal significance is the Skylab finding that the total magnetic flux contained in bright points is at least as great, and possibly greater, than that customarily assessed in counts of sunspots and active regions. Because magnetic activity rules the Sun, bright points may indeed prove to be the most important feature of the star. If that is so, in counting sunspots and plotting sunspot numbers, solar astronomers may long have been distracted.



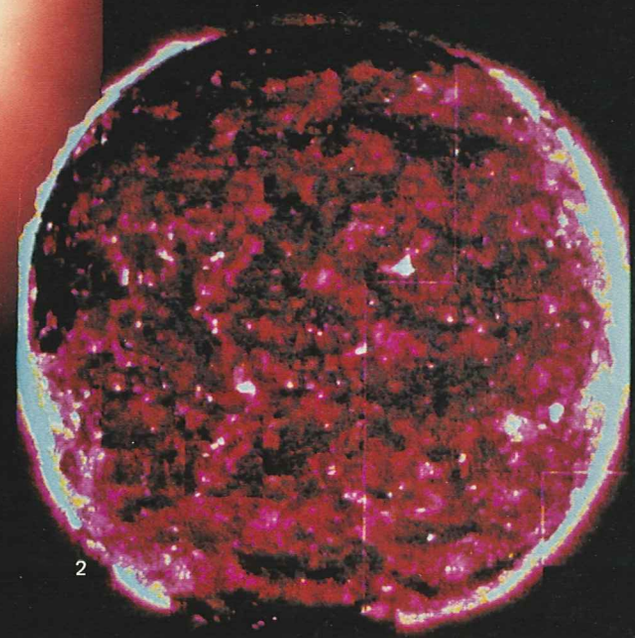


1

FIRST SEEN IN X-RAY PICTURES, scores of bright points of light dot the solar disk, like scattered jewels. The glittering points (1) are found all over the Sun and are not limited to lower latitudes where the large-scale active regions lie. Nor are they absent in coronal holes. Detailed comparison with magnetic maps of the Sun show that X-ray bright points overlie compact magnetic regions that have both positive and negative polarity. Bright points come and go, lasting on the average about 8 hr. Some last for several days; others flare up and fade in a few minutes. At any time, 100 or more can be seen on the visible hemisphere of the Sun. Because there are so many bright points, they account for much of the Sun's magnetic energy.

SKYLAB found that bright points dot the ultraviolet Sun as well, when seen in wavelengths that sample the transition region and corona. Here at coronal temperatures (2), bright points are found to coincide with bright fragments of the chromospheric network, where magnetic field is concentrated.

When plotted on a map of the Sun (3), X-ray bright points show a slight preference for middle latitudes, and seem equally at home in active regions, coronal holes, or the undisturbed Sun. Individual bright points observed in X-ray images of the Sun during the first Skylab mission are shown in this map as single dots. Outlines of coronal holes seen during the same 28 days are also drawn in, and active regions are shown as squares.



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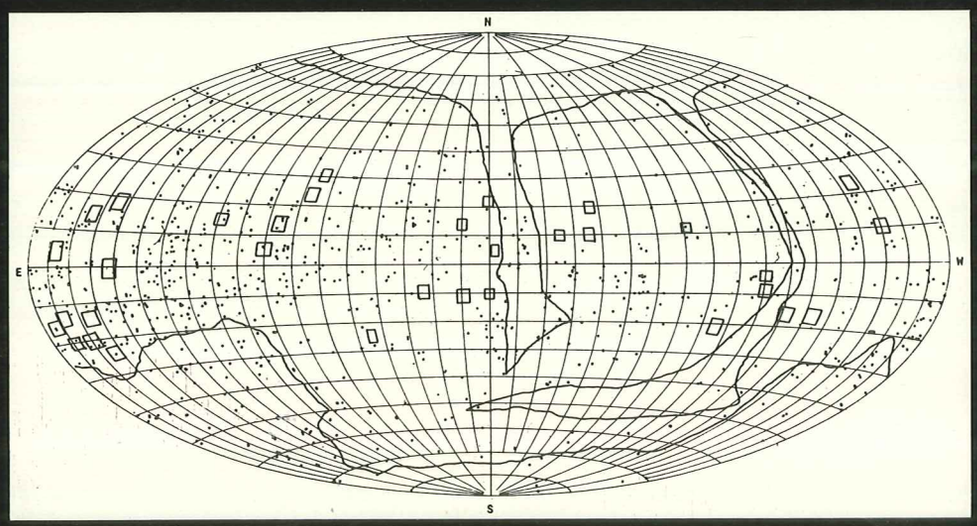

3

BRIGHT POINTS in the ultraviolet (4) are related to patterns of magnetic field (5) concentrated at boundaries of super-granule cells in the chromospheric network. Color-coded ultraviolet pictures (4) of a small area of the solar surface distinguish chromosphere (blue), transition region (red), and corona (green) contributions. Green corona is absent in a sprawling, red and blue coronal hole. Within the hole, and elsewhere in the area, bright, circular patterns outline the boundaries of super-granule cells. Bright (white) points fall on the network super-granule cell boundaries.

Magnetic map of the same area (5) delineates the same patterns, cell-for-cell, and ties bright points to magnetic concentrations at super-granule cell boundaries. Concentrated magnetic fields are shown in the magnetogram in red for one polarity and in light blue for the opposite polarity. In this area of the Sun, super-granule cell boundaries are predominantly red.

4

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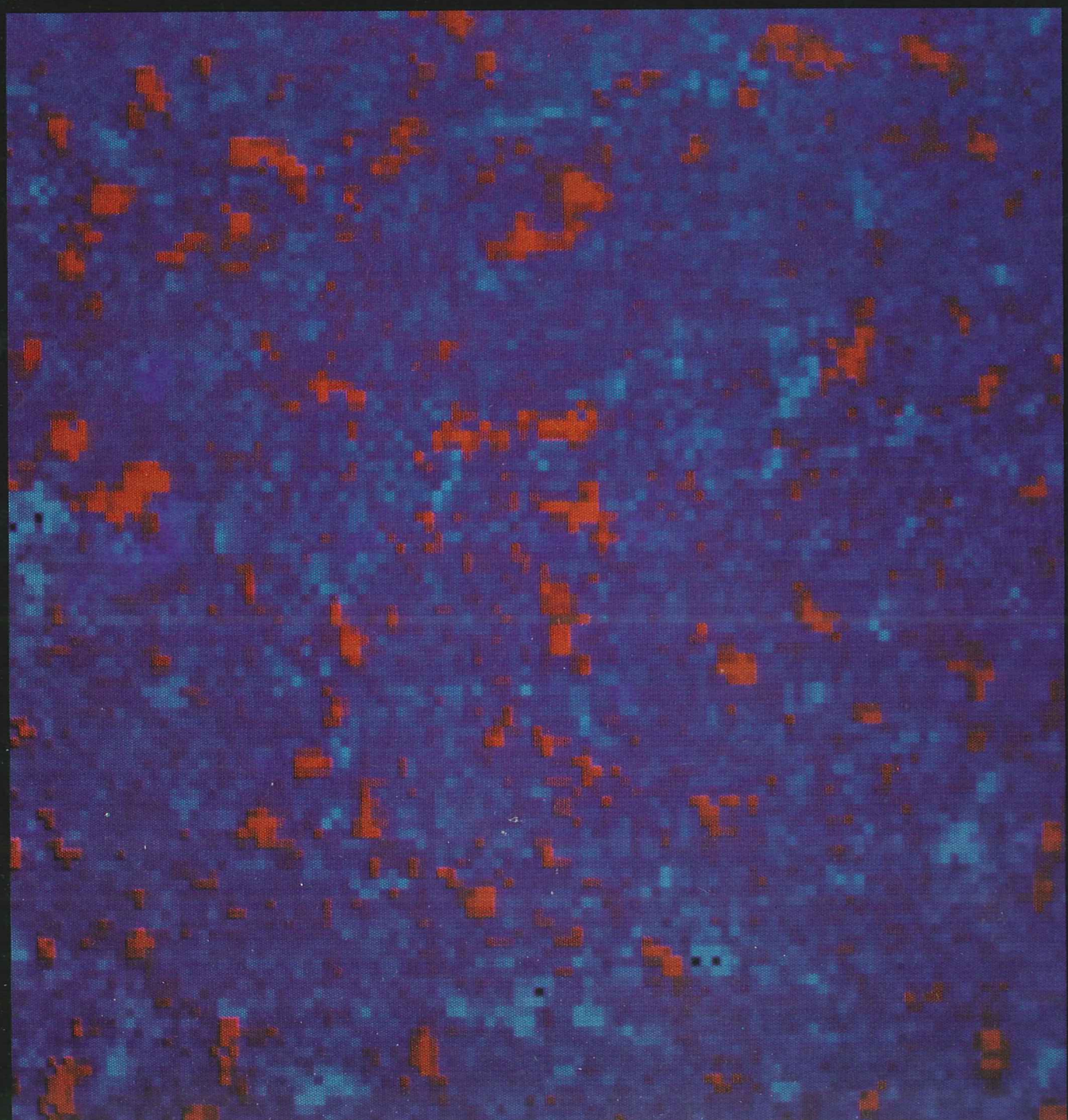
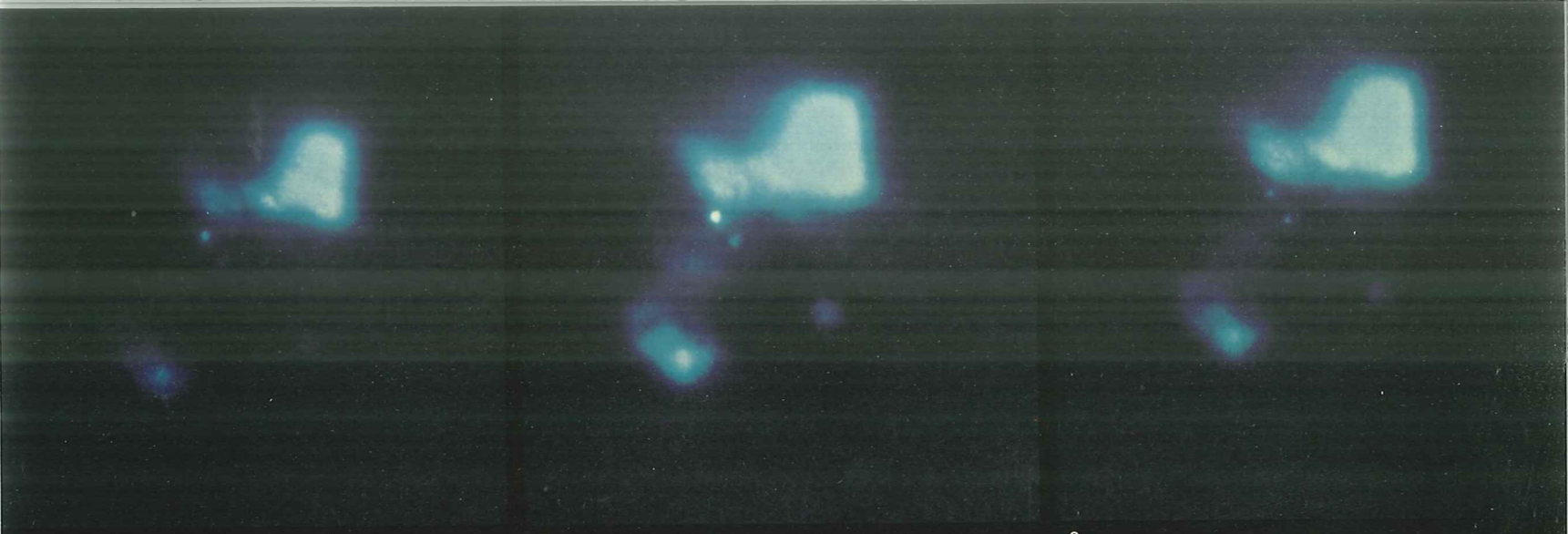




1 2 3

(1-6) A PAIR OF X-RAY BRIGHT POINTS flash alternately off and on, as in a lighted warning sign. Then a whole arcade of loops brightens, revealing that short-lived bright points also appear in the legs of individual X-ray arches. The sequence (1-6), made in hard X-rays that sample temperatures of 3 to 5 $\times$ 10^6 K, covers an interval of only 17 min. Hazy X-ray emission from the bright regions at top and bottom of each picture, more typical of what is seen in the quiet corona at these high temperatures, contrasts the minute size of X-ray bright points, where energy is highly concentrated. Throughout the display, bright points, which in this case resemble small solar flares, are more intense than any other feature.

(7) NEAR THE SUN'S SOUTH POLE a point of light the size of Earth suddenly brightens, calling attention to itself in a large coronal hole. Flaring bright points like this, unseen before Skylab, constitute a class of small flares that, unlike more common flares seen in active regions, appear all over the disk of the Sun.

8, 9, 10

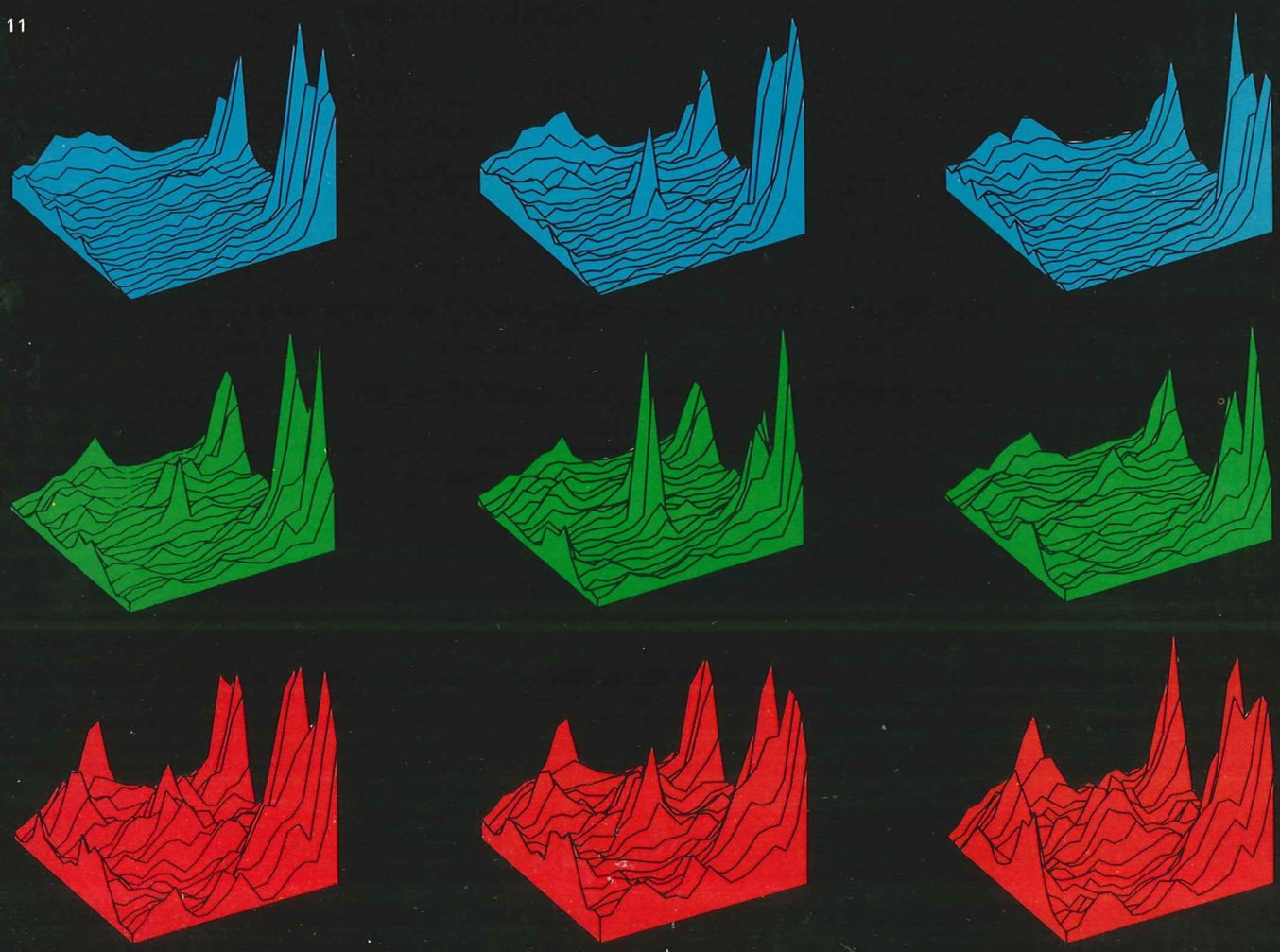
7

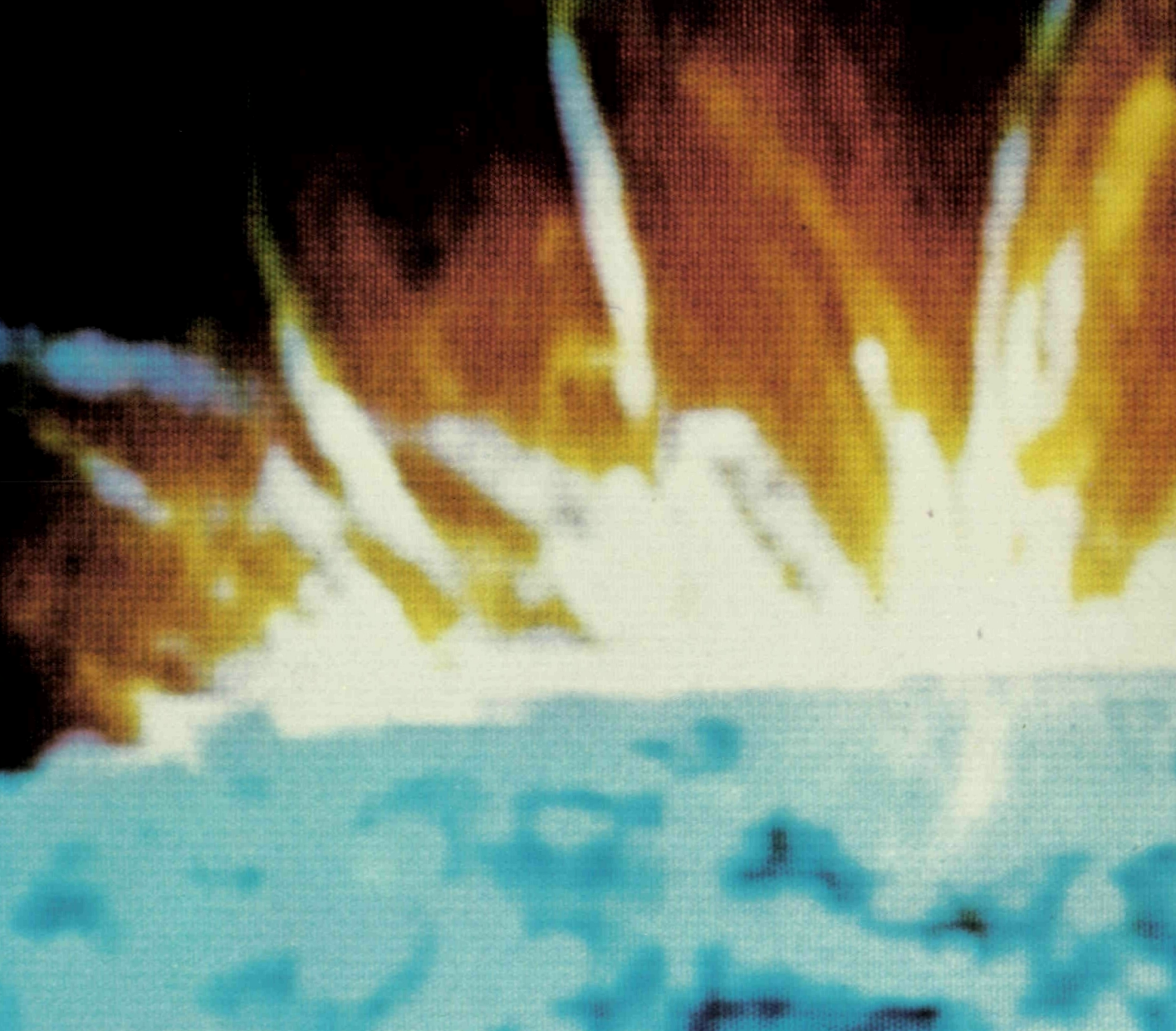
4 5 6

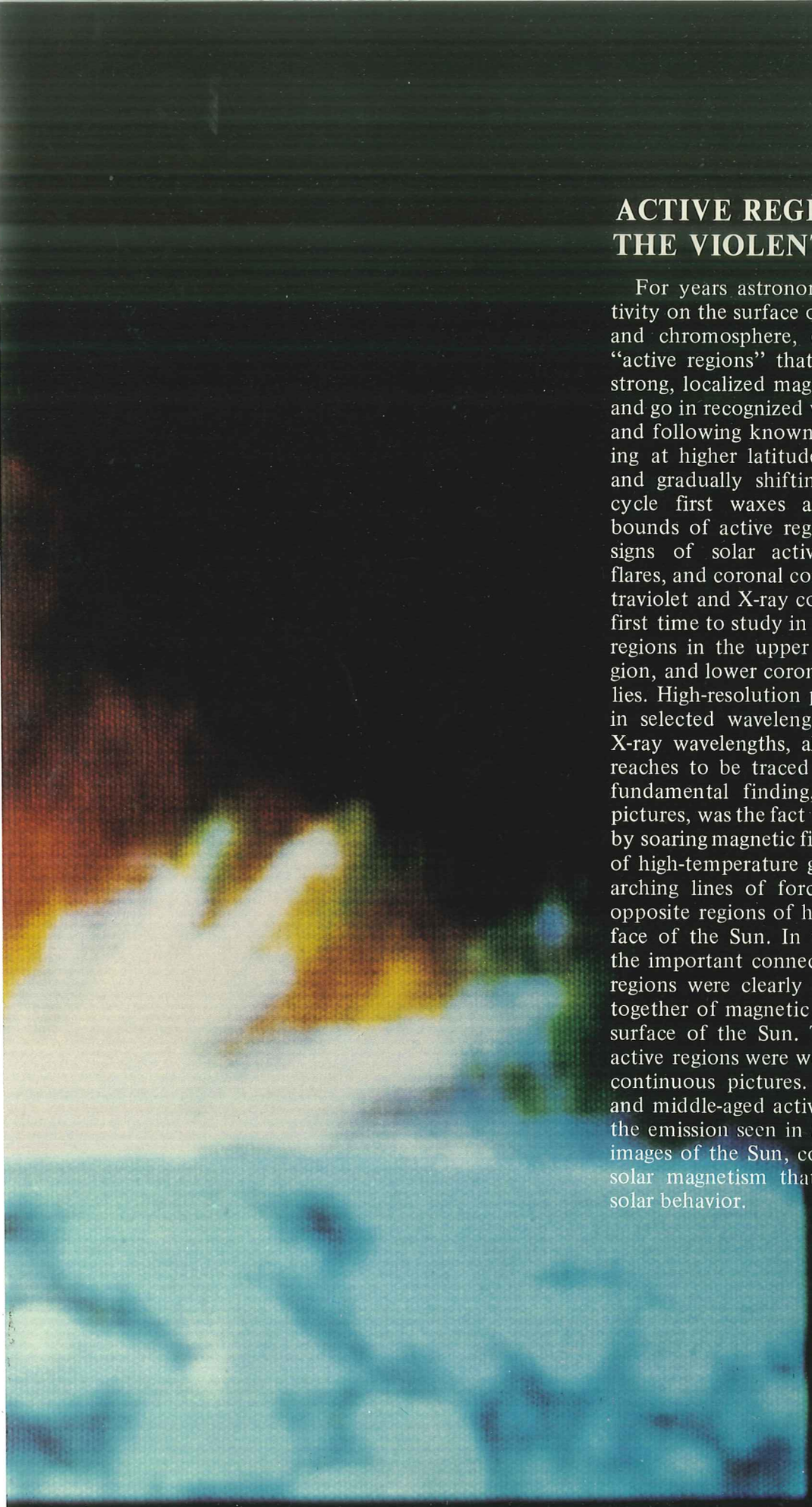
ANOTHER FLARING BRIGHT POINT (8-10) flashes out in X-ray pictures taken about 12 min apart. This example also occurs in a polar coronal hole, near the limb of the Sun, where we see it in slanting view.

AN ULTRAVIOLET BRIGHT POINT, portrayed simultaneously in three wavelengths (11), rises and falls in brightness in a few minutes. Here brightness is shown as a contour map of a small area of the solar surface; brighter features appear as spikes. Bottom row (red) portrays chromospheric temperatures, the middle row (green) portrays the transition region, and the top row (blue) portrays the 1.4×10^6 K temperatures of the corona. Red, green, and blue pictures in each column were made at the same instant, in three samples taken 5 min apart. The bright spike that comes and goes in the center of each contour map is from a small area about the size of Earth. Barely distinguishable in the chaotic chromosphere, it is most spectacular in the transition region, and a distinct feature of the corona, where it would also be seen in X-rays. Skylab found that most bright points do not flare up like this sample, but live more constant lives.

11

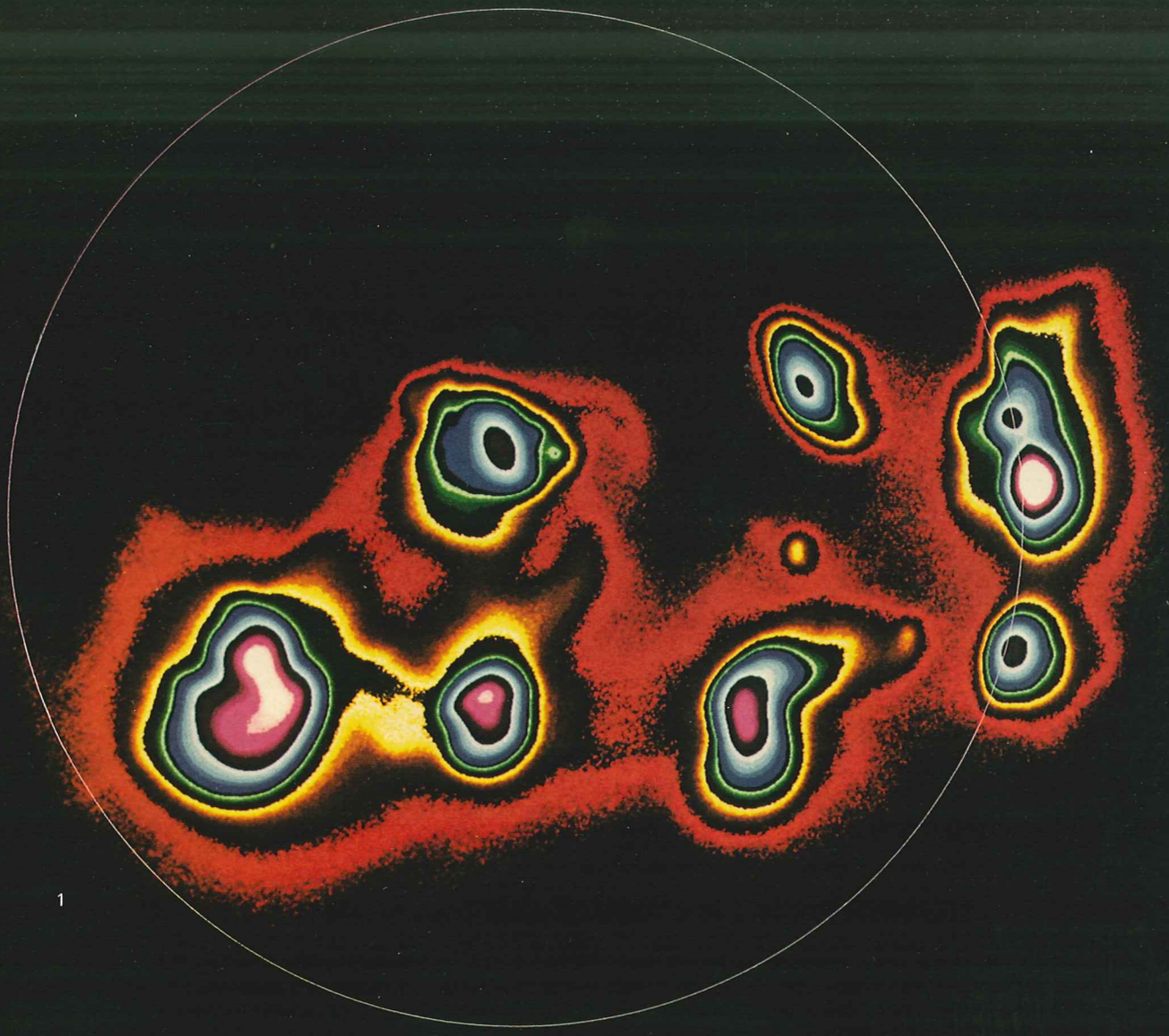






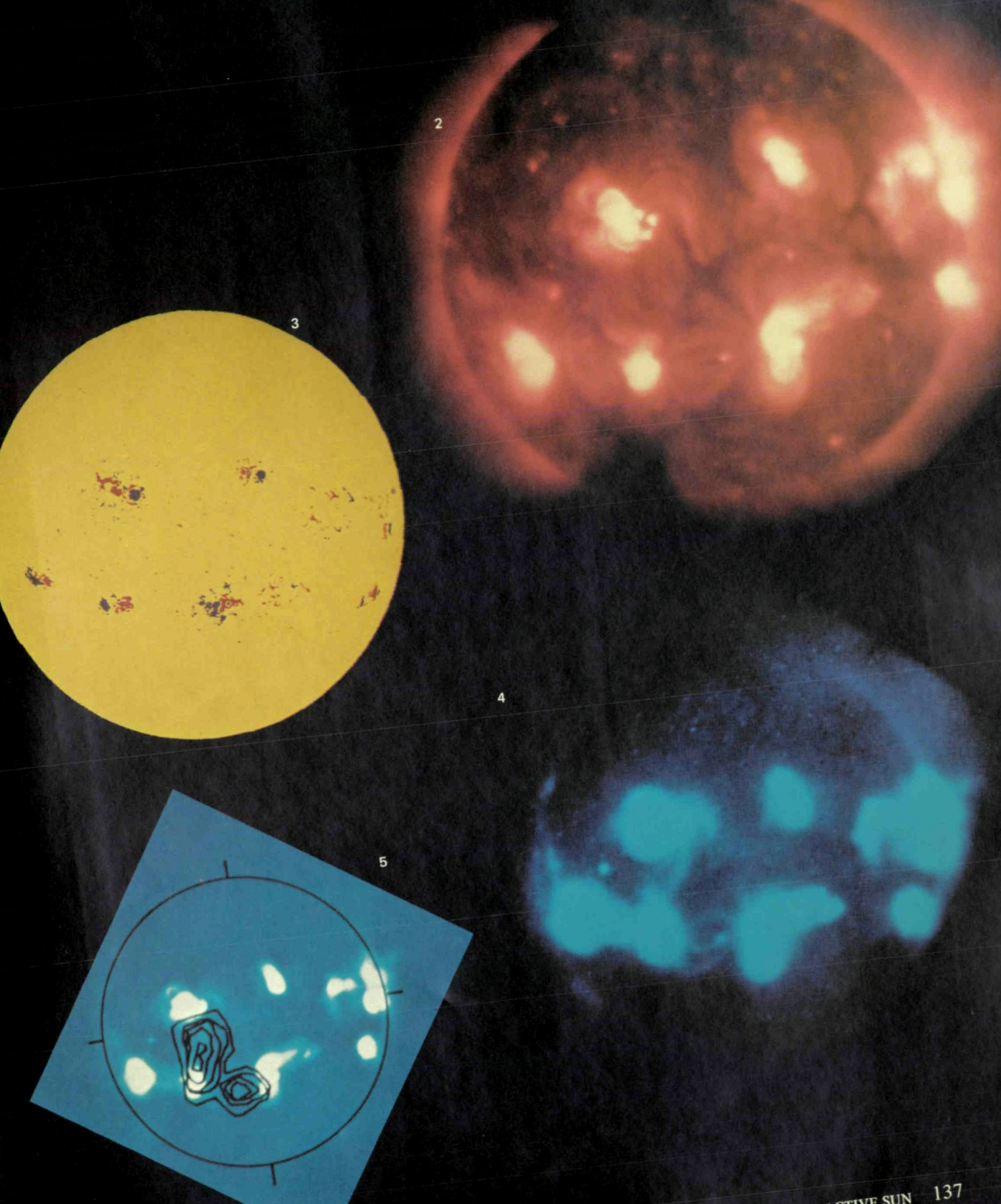
ACTIVE REGIONS: THE VIOLENT SUN

For years astronomers have recognized that activity on the surface of the Sun, in the photosphere and chromosphere, evolves in local areas called "active regions" that are associated with areas of strong, localized magnetic fields. These fields come and go in recognized ways, lasting weeks or months and following known patterns on the Sun: appearing at higher latitudes early in the sunspot cycle and gradually shifting toward the equator as the cycle first waxes and then wanes. Within the bounds of active regions are found all the classic signs of solar activity: sunspots, prominences, flares, and coronal condensations. With Skylab's ultraviolet and X-ray coverage, it was possible for the first time to study in detail the extensions of active regions in the upper chromosphere, transition region, and lower corona, where most of their energy lies. High-resolution pictures, made simultaneously in selected wavelengths in the ultraviolet and in X-ray wavelengths, allowed their important upper reaches to be traced in detail before unknown. A fundamental finding, apparent in all the Skylab pictures, was the fact that active regions are defined by soaring magnetic fields; they consist of hot loops of high-temperature gas, trapped and contained by arching lines of force whose footpoints stand in opposite regions of high magnetic field on the surface of the Sun. In the ultraviolet and in X-rays, the important connections between these magnetic regions were clearly revealed, including the lacing together of magnetic regions often far apart on the surface of the Sun. The birth and death of solar active regions were well observed in Skylab's net of continuous pictures. Magnetic loops in new, old, and middle-aged active regions account for most of the emission seen in Skylab's ultraviolet and X-ray images of the Sun, confirming the feeling that it is solar magnetism that calls the tune of changing solar behavior.



1

REGIONS OF MOST VIOLENT ACTIVITY on the Sun are restricted to two parallel belts on either side of the solar equator; at the beginning of each 11-year solar cycle they appear at about 45° solar latitude and gradually converge toward the Sun's equator. At the time of Skylab's flight, late in the declining solar cycle, active regions were found in the two low-latitude bands shown here (1-5). In hard (1, 4) and soft (2) X-rays, individual active regions stand out in sharp contrast, illustrating that they are areas of locally high temperature. In (1) brightness is color-contoured from the hard X-ray photograph (4), with brightest shown as white. White regions correspond to local temperatures in excess of 5×10^6 K, a thousand times hotter than in the photosphere below, where the same active regions appear as cool sunspots. In a simultaneous magnetic map of the Sun (3), we see the same active regions in the photosphere as strong magnetic fields of opposite polarity, here coded red and blue. At coronal temperatures sampled in X-ray photographs (2, 4), active regions are revealed as fuzzy loops that connect these areas of opposite magnetic polarity. The tops of the loops are also the source of varying radio noise from the Sun, as seen in (5), where a map showing locations of bursts of radio static from the Sun is overlaid on the X-ray photo (4). The Sun is a constant emitter of radio waves—the most intense and variable of which can be traced with radio telescopes to active regions, where trapped electrons bounce back and forth along the arched loops, emitting static as they go.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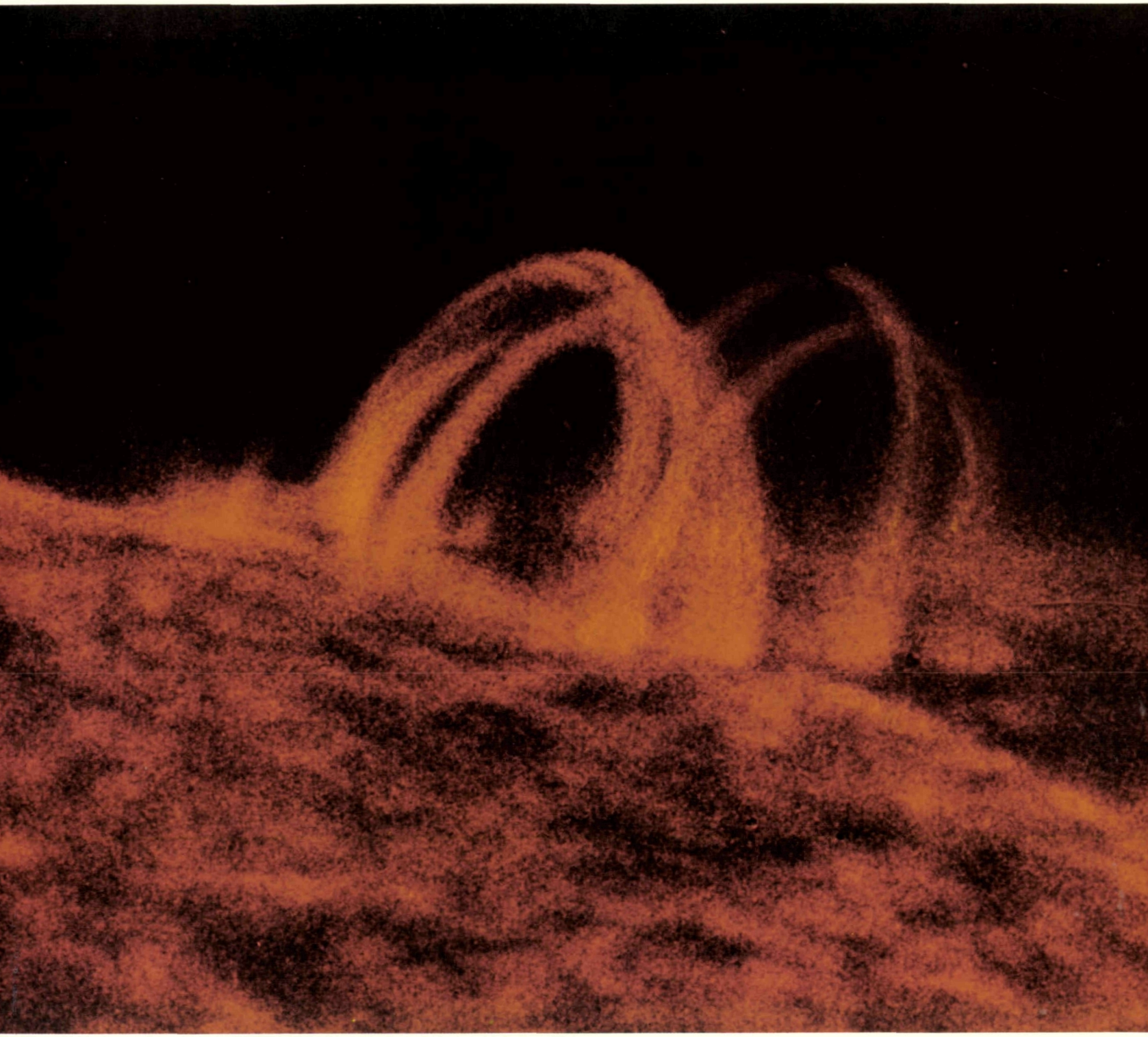
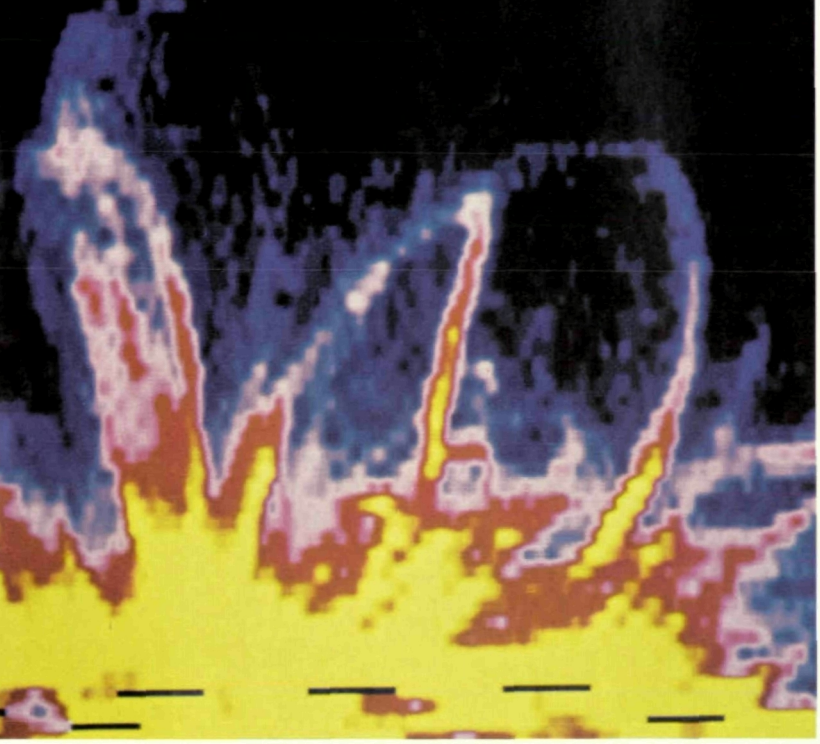
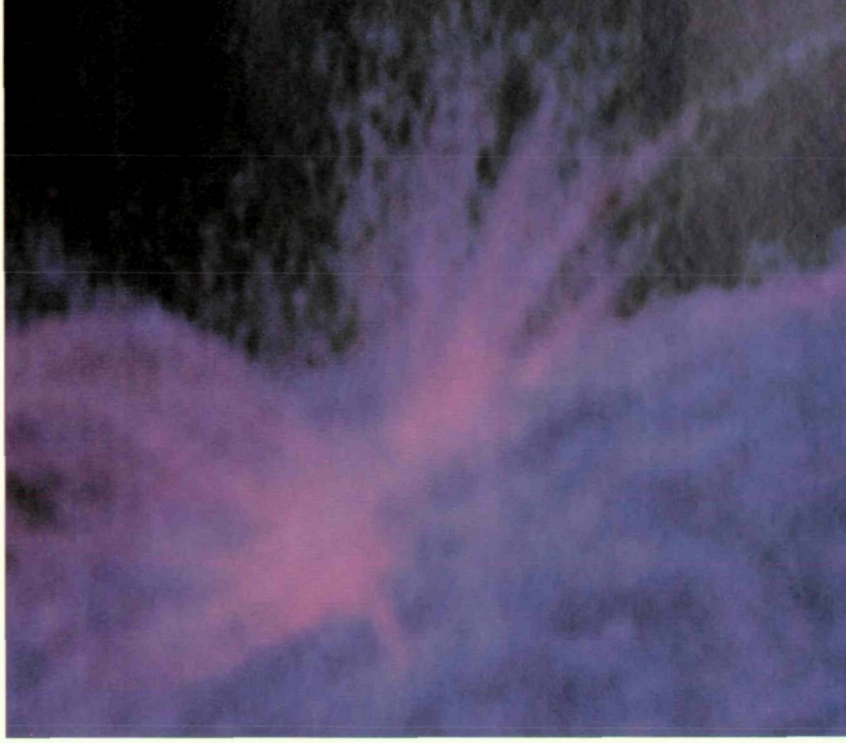
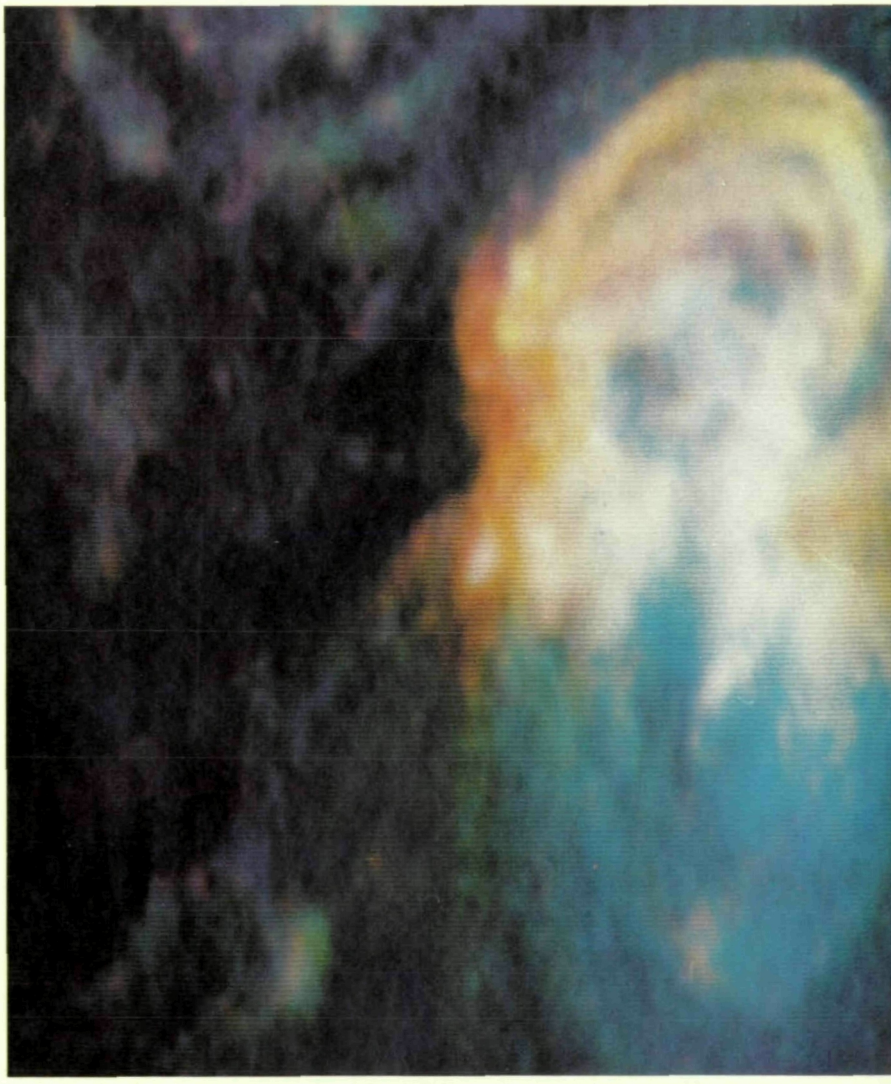
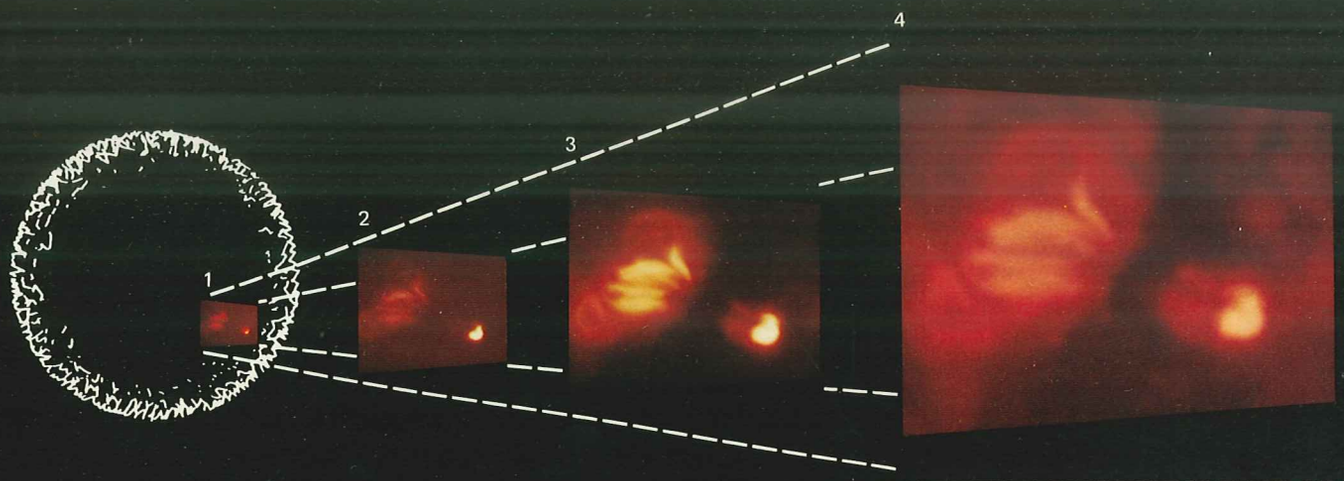


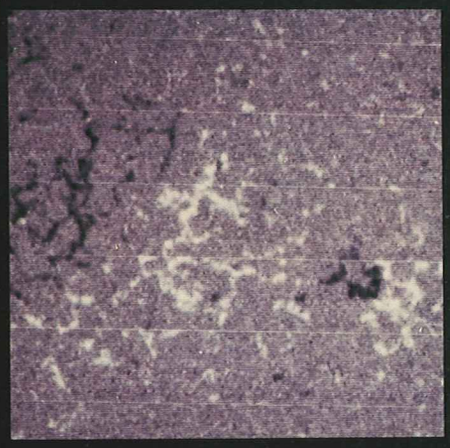




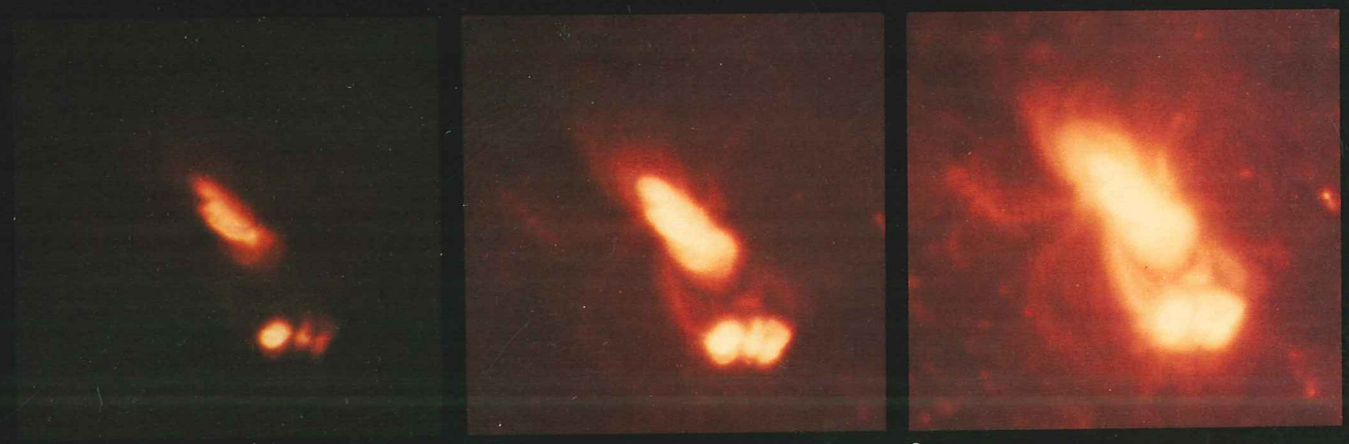
SKYLAB ULTRAVIOLET PICTURES disclose the patterns of magnetic loops that hold hot, ionized gases above all solar active regions.







CLOSE-UP X-RAY VIEWS from Skylab (1-4) reveal systems of loops that lace together areas of intense opposite magnetic polarity on the surface of the Sun; these areas appear in an accompanying magnetogram (5) as light and dark patches. Magnetic fields on the Sun are far stronger than that of Earth, and are created and maintained by large-scale motions in hot ionized gas. In active regions the fields and loops bottle up prodigious stores of energy, which from time to time are suddenly released in violent eruptions and solar flares. Solar eruptions in turn affect our Earth, when bursts of high-energy radiation and clouds of charged electrons, protons, and other atomic particles are received from the Sun.



PROGRESSIVELY LONGER X-RAY EXPOSURES (6-8) bring out the magnetic loops that stitch segments of a solar active region together. The shortest exposure (6) shows only the intense emission from the innermost loops. In this small area of the solar surface, about the size of Jupiter, a tangle of magnetic loops is seen near the limb of the Sun. Some errant lines in the longest exposure (8) arch over to outlying bright points and magnetic clumps in the surrounding network.

9

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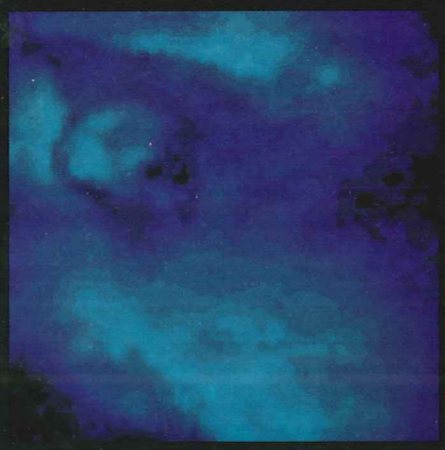

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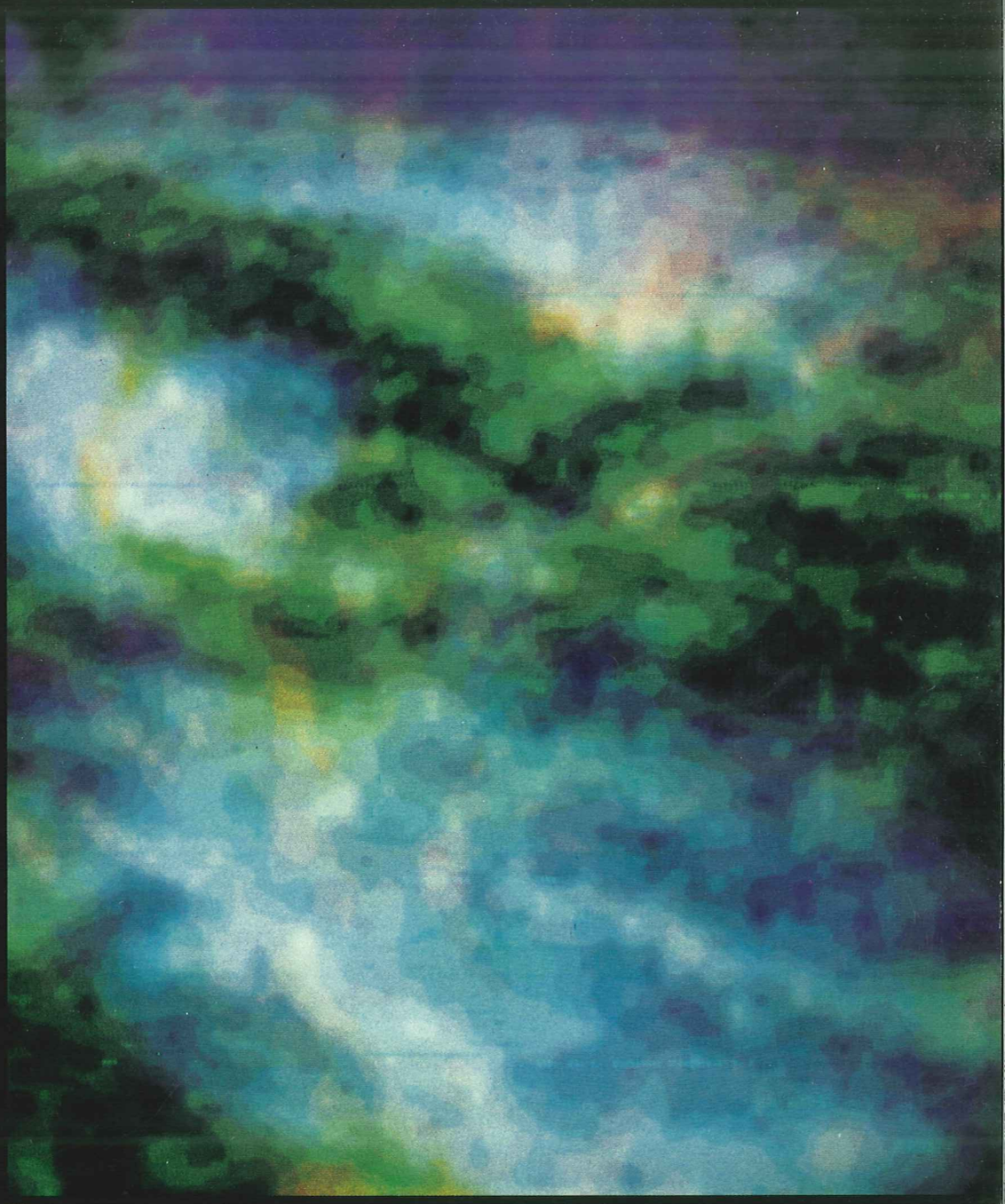

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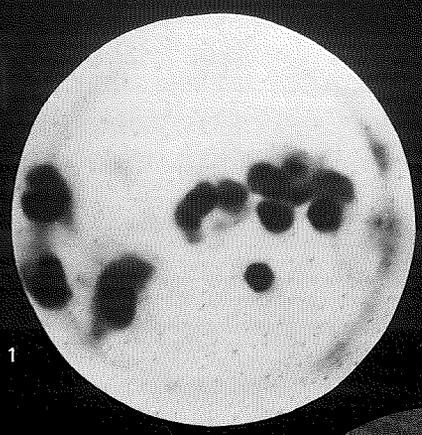
ULTRAVIOLET DISSECTION OF ACTIVE REGIONS near the limb paints a colored picture of the hot loops that arch high into the solar atmosphere. Here light from the low chromosphere (9) is colored green; from the transition region (10), red; and from the corona (11), blue. In the larger photo (12) the three pictures and colors are added together. The set of active region loops is too hot to be visible at (green) chromospheric temperatures and too cool to show up sharply in the hotter blue corona, where we see only the diffuse envelope of their outer sheaths. Temperatures in the transition region (red) are just right, and by sampling temperatures of about 450 000 K (10), we see loops most distinctly. Sequences like this from Skylab enabled solar scientists to pinpoint temperatures and other conditions in the roaring solar atmosphere 150 million km away.



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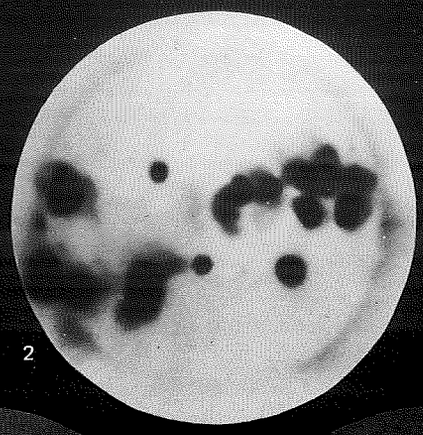

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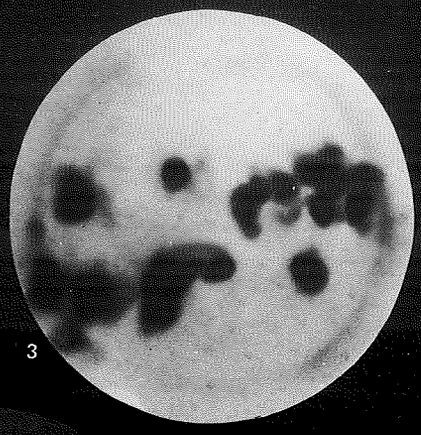

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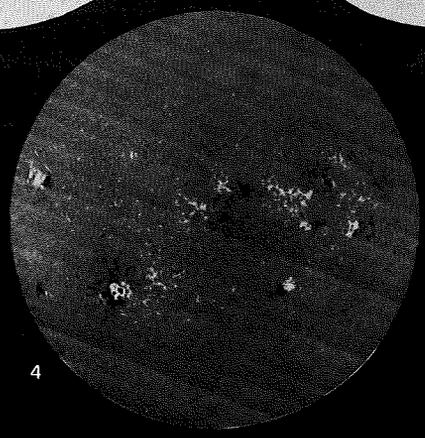
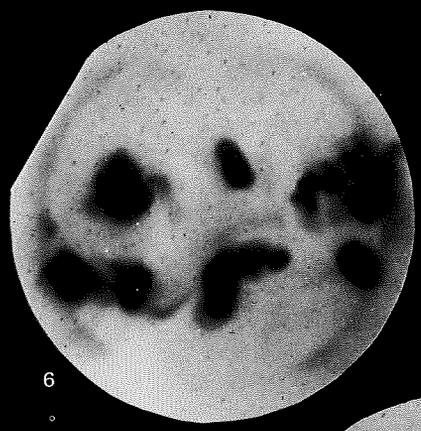


4

5

THE BIRTH OF TWIN ACTIVE REGIONS was witnessed by the Skylab X-ray telescope. Sequence (1-3) covers a day and a half in the life of the Sun. Here X-ray pictures sampling coronal temperatures of 3 to 5 $\times$ 10^6 K are printed as negatives, with black indicating bright emission, and white as cooler areas. In one day, between (1) and (2), two black patches of X-ray emission appear, each about the size of Earth, to the left and slightly above and below the center of the Sun. As the lower one is born, looping arms reach out from an older, larger active region on its left, as though to clasp it to the Sun. By (3), a half day later, the ties are complete. Magnetograms (4, 5) taken about midway between the three Skylab X-ray pictures show that both newborn active regions consist of adjacent positive (white) and negative (black) areas of solar magnetism that have risen from within the Sun to break through the surface of the photosphere.



6

TWO DAYS LATER, between (6) and (7), another new active region emerges, as a smaller dot of X-ray emission just below the center of the Sun; it is also connected by magnetic loops to older, active regions. Between the two exposures, made about 12 hr apart, X-ray loops in other regions (left of center) arch across the solar equator to connect active regions in northern and southern latitude bands. The connected regions in the photosphere lie over the solar horizon from each other, as far apart as the Moon and Earth. Had this connection occurred at the limb of the Sun, we would have seen it as a gigantic coronal arch that straddled the solar equator. A magnetogram (8), made shortly after (7), identifies the magnetic areas that are laced together by hot X-ray arches in (6,7).

7

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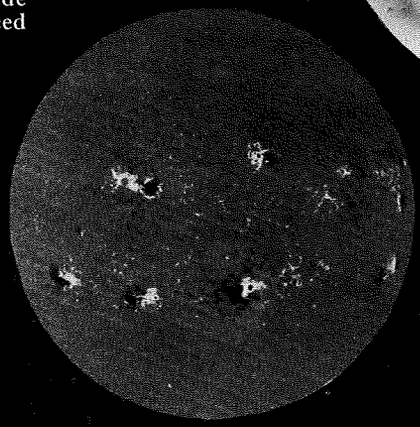

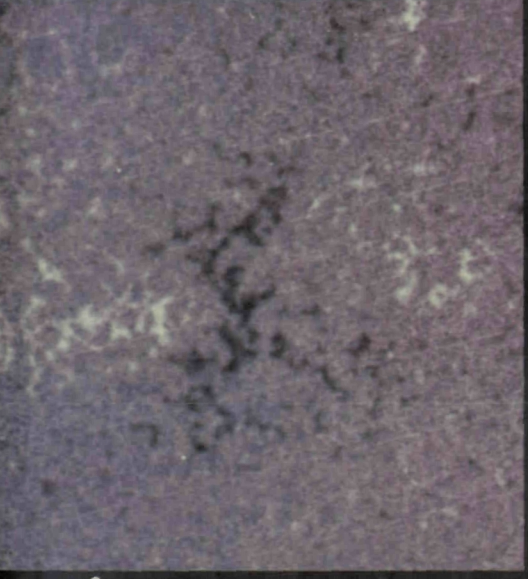

9

AS SKYLAB WATCHES, a solar active region dies, much more slowly than it was born. X-ray loops gradually spread and fade, like smoke from a dying fire, in pictures (10-12) spaced about 27 days, or one solar rotation, apart. A magnetogram (9), made on the same day as (10), shows in light and dark patches the areas of opposite magnetic polarity in the photosphere that are connected by the X-ray loops. An H_α picture (13), made on the same day as (9) and (10), portrays the same region in the chromosphere. H_α sequence (13-15), made in step with the X-ray pictures above it, documents the parallel fading and disappearance of the active region in the lower chromosphere. X-ray loops preserve the longest memory of a solar active region, lingering as faded, ghostly loops long after the end of its life in chromospheric layers below.

10

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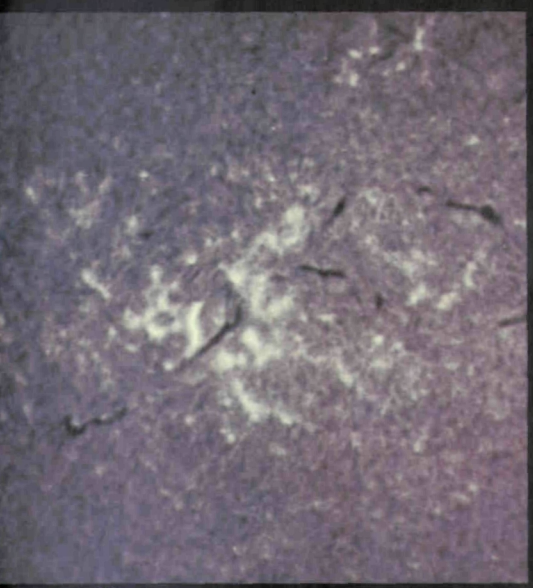

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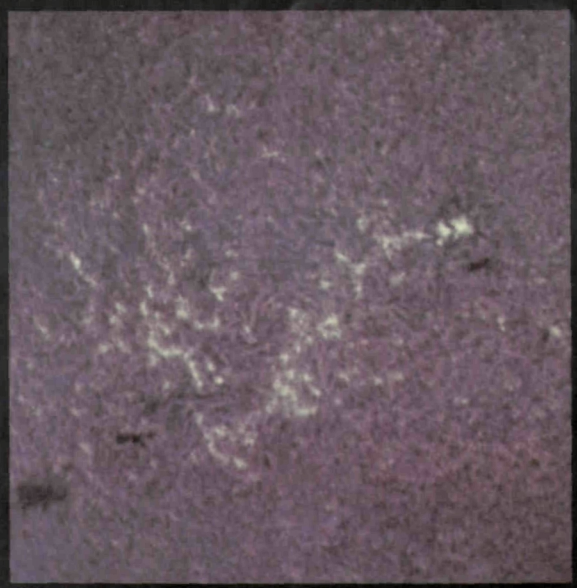

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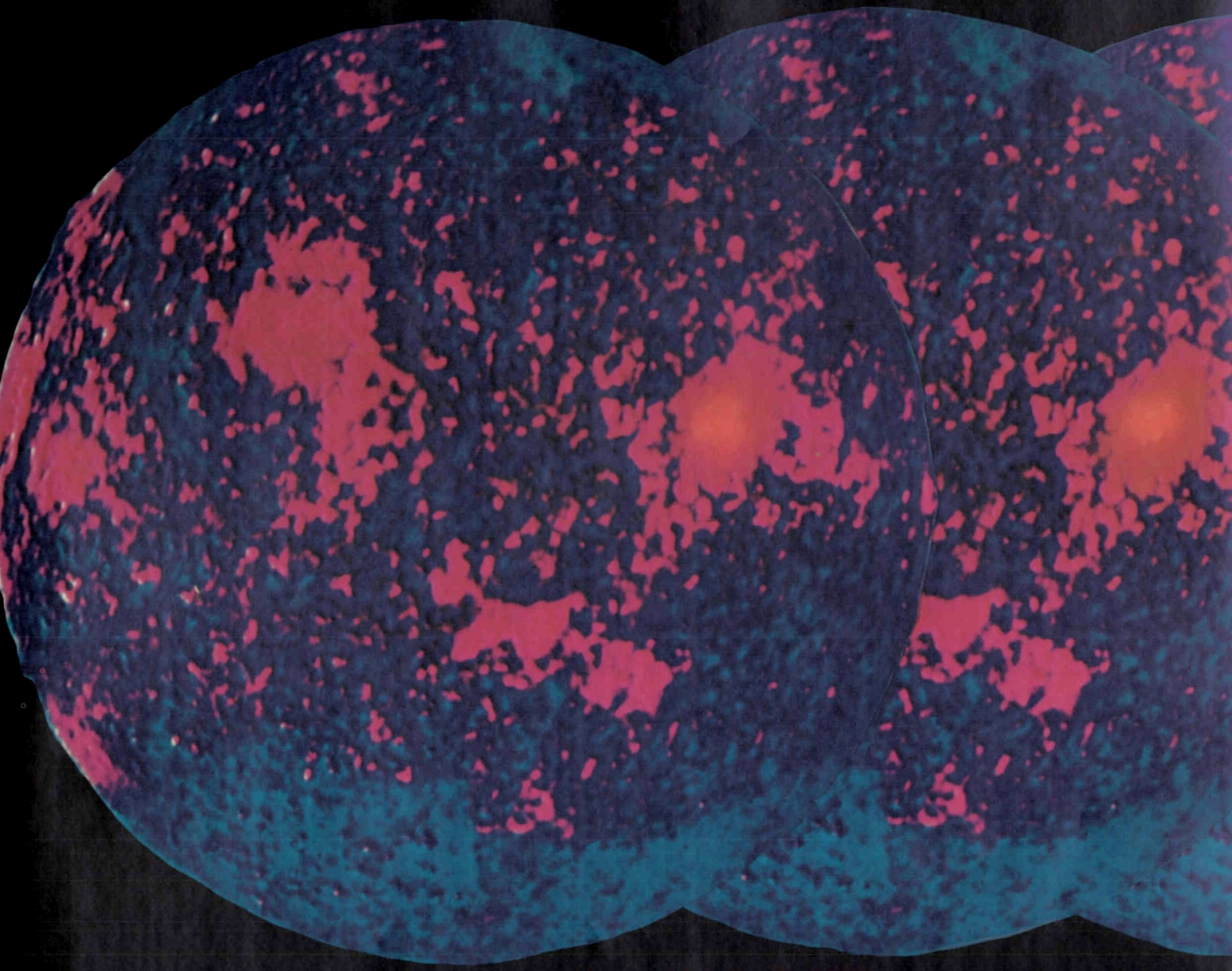
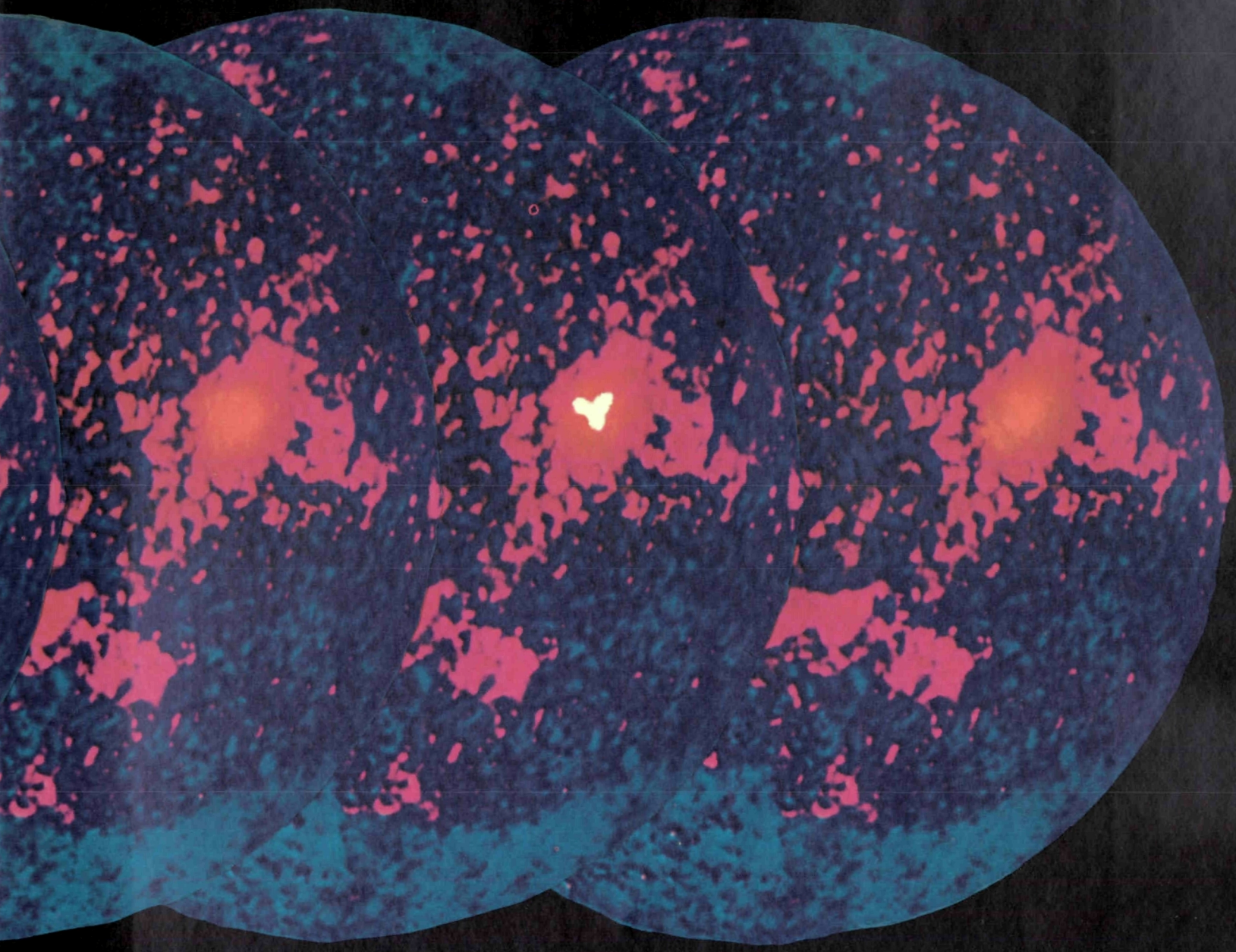


FLARES: THE EXPLOSIVE SUN

Solar flares are the most powerful and explosive of all forms of solar activity and, as might be expected, the most important in terrestrial effect. For many years astronomers have watched for them in the chromosphere, where they appear as sudden and generally unexpected brightenings, lasting from a few minutes to half an hour, usually in strong or complex magnetic regions. In the chromosphere they appear much like a pool of gasoline that has suddenly been ignited. Flares are more than flashes in the pan. Atomic particles released from the Sun during larger flares sweep against our upper atmosphere, disturbing Earth's magnetic field, disrupting the ionosphere and radio communications, and causing auroras and other effects.

For some time it has been known that ultraviolet and X-ray radiation from the Sun increases dramatically during flares, causing other important effects in our upper atmosphere. These increases suggested that flares were high-temperature phenomena whose secrets would be found in the higher, hotter regions of the solar atmosphere. Thus a prime objective of Skylab's solar observing program was the observation of the complete behavior of flares in X-ray and ultraviolet wave-



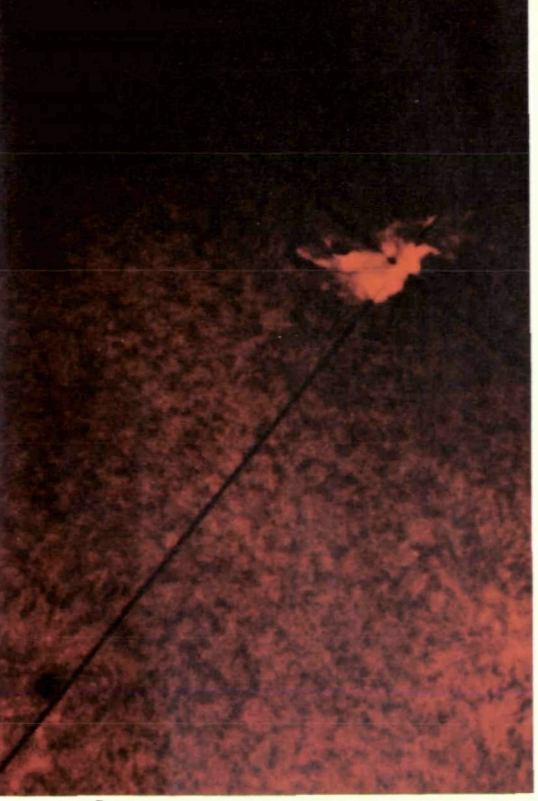
lengths, taking advantage of Skylab's position above the atmosphere of Earth and its unprecedented ability to see fine details on the Sun in these hidden wavelengths.

Many solar flares were observed in detail by Skylab, including the crucial early phases that give new clues to the sources of their energy and its explosive, sudden release. Ultraviolet spectra taken of different flare phases revealed the existence of localized temperatures within flares that exceeded 20 $\times$ 10^6 K, as hot as conditions in the searing interior of the Sun. High-resolution pictures made in hard X-rays revealed an unappreciated confinement of the initial flare disturbance to intensely heated regions so small that they taxed the resolving power of Skylab's telescopes. In several important cases, X-ray and ultraviolet observations demonstrated that the important seat of flares lay in the tops of small, intense magnetic loops and that certain flares consisted of the sequential brightening of loops in a series, or arcade, like the popping off of a string of solar firecrackers. Energy released in flares in the ultraviolet and X-ray wavelengths was far greater than the emission seen customarily from the ground in visible wavelengths, confirming that what was seen of them in the past was but a fraction of their most important features.

WHEN OR WHERE flares will occur is not known in advance. This made Skylab's chances of observing a flare less certain. Moreover, because Skylab was launched late in the solar cycle, when the general state of solar activity was low, no one was sure that it would see any large flares at all. It was hoped that several would occur, and that through rapid communications and quick reactions by the astronaut crews, at least one could be caught in the sights of Skylab's battery of solar telescopes.

The Sun obliged by producing many flares, of all sizes; more than 100 smaller flares were caught in Skylab's net of routine observations of the entire disk of the Sun in X-rays. When rapid responses and precise pointing were required for taking spectra and other more detailed observations of flares, Skylab's alert crews time after time brought home their quarry, as revealed in the record of Skylab H_α pictures (2-7), that document where Skylab's telescopes were pointed during six of the larger flares. At the telescope control console (8) is one of the flare hunters, Astronaut Bill Pogue.

1



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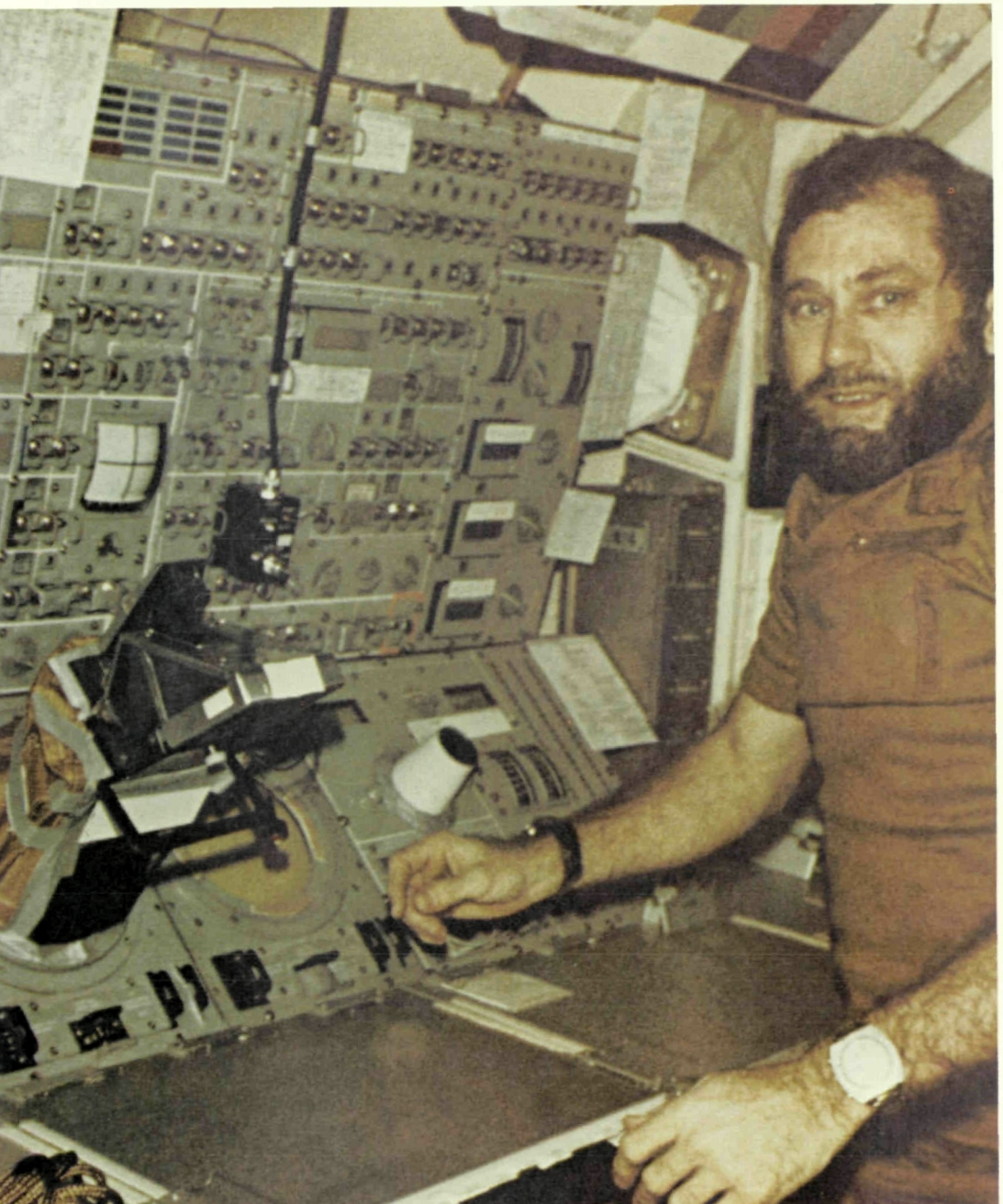

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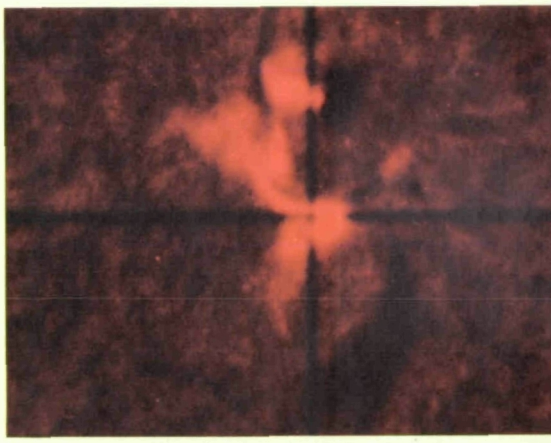

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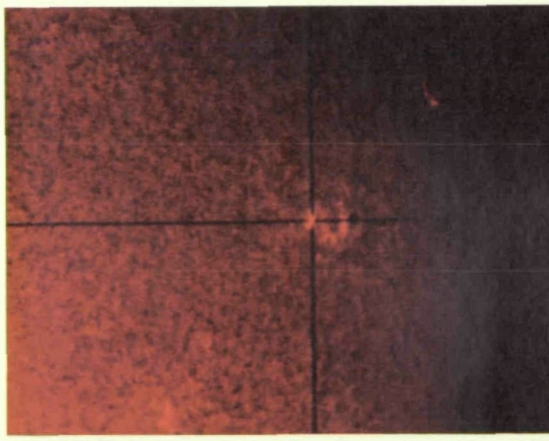

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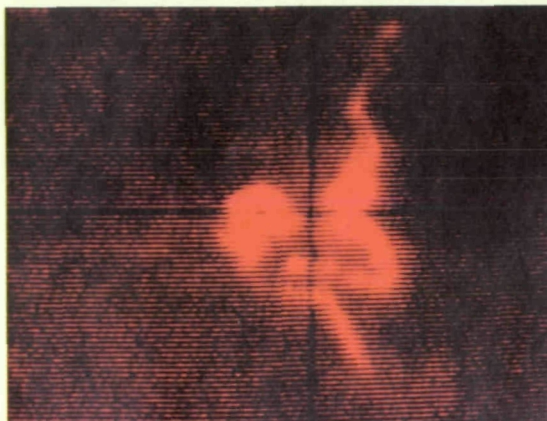
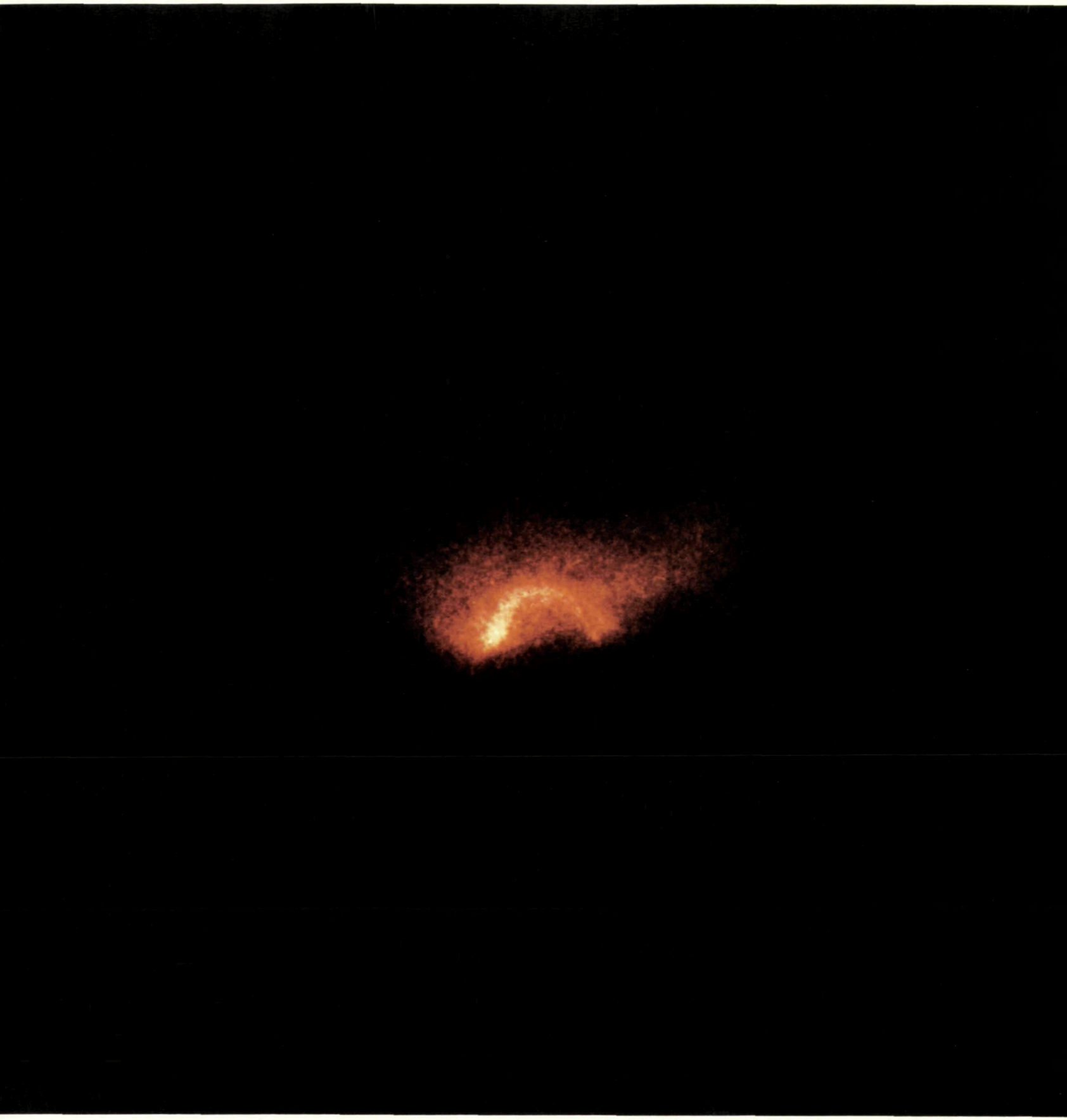
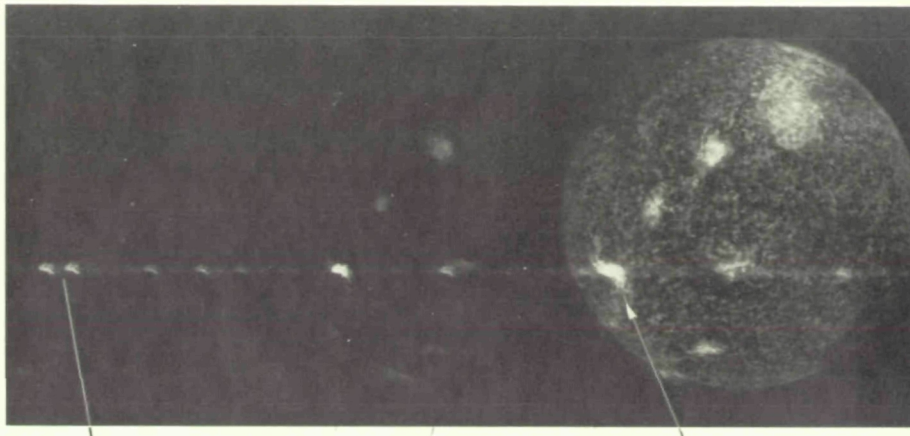




1

A PRIME OBJECT in Skylab's hunt for flares was the answer to a simple question: What does the start of a flare look like in the high-temperature regions of the solar atmosphere—above the level where we see them as spreading fires in the chromosphere? What strikes the match that sets off the inflammable pool? Sought was the secret of what causes solar flares and, from this, better predictions of when and where they will occur.

Skylab's telescopes found that in X-rays (1) flares are triggered by the brightening of small, low-lying loops in active regions. X-ray flares began in tiny areas of individual loops, as smaller features than many would have guessed. But like the quick, small flash in the sparkplug of an engine, these intense brightenings set off other, larger effects. The spreading flares seen by Skylab in H_α were aftereffects of initial disruptions in hot coronal loops, where momentary temperatures exceeded 20×10^6 K—hotter than in the core of the Sun itself where, in denser material, nuclear reactions occur.



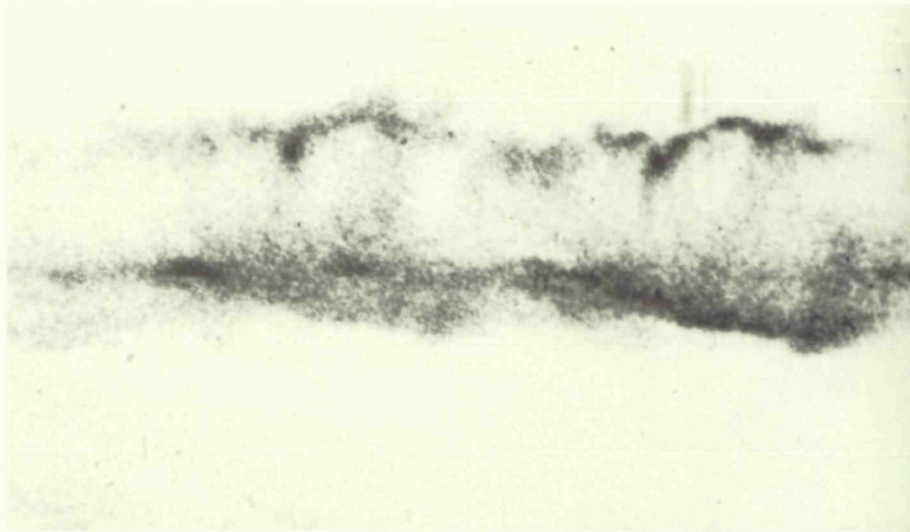
2

Flare

ULTRAVIOLET PICTURES from Skylab (2,6) spread a flare out in wavelength, like a deck of cards, to find what it looks like at different layers and temperatures. At chromospheric temperatures (full disk in (2)), the flare is a double ribbon, much as it appeared in slightly cooler H_α. To the left in (2), spread along the bright horizontal streak, we see simultaneous images of the same flare in several other spectral lines, sampling hotter temperatures more typical of the corona. Enlargements of the last two images of the flare in (2) are shown in which, at temperatures of 3×10^6 K (3) and 2×10^6 K (4), we see that it is an arcade of brightened loops whose opposite footpoints rest on the chromospheric ribbons. These views (2-4) sample the flare slightly after its hottest stage.

3 4

A FLARE at the limb of the Sun (5,6) affords an edge-on view of the loop where it all began. These negative prints show bright regions as black. In (5), three overlapping ultraviolet images of the flare are strung out in wavelength. They sample temperatures, left to right, of about 3, 14, and 2×10^6 K, from iron vapor which in the hot inferno of the Sun has been stripped of most of its 26 electrons. A bright ribbon runs along the footpoints of an arcade of bright-topped loops. Nestled under the loops, and seen best in the higher temperature lines, left, is a small, low-lying loop where the flare began. Other spectral pictures of the same flare (6) show the same low-lying loop at even higher temperatures, in the light of iron vapor at 17 million K, which has but three electrons left, and that of calcium ionized 16 times at about 5 million K.



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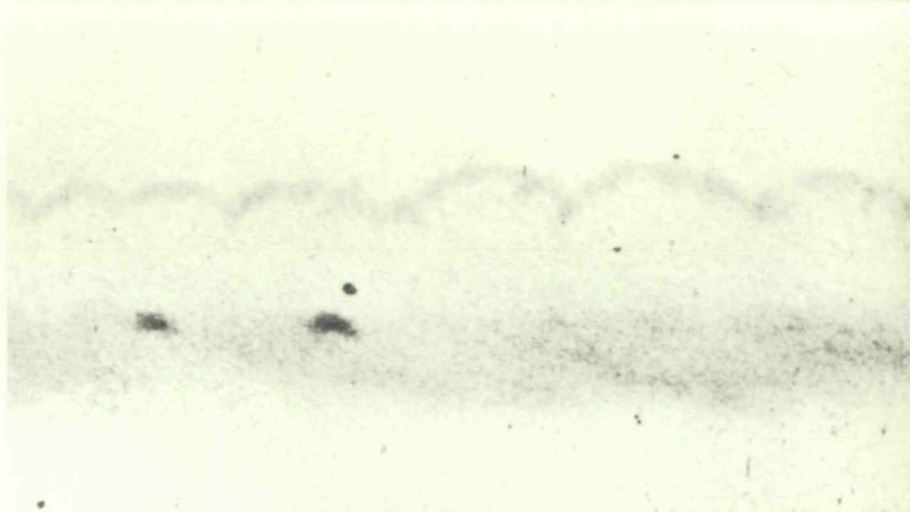

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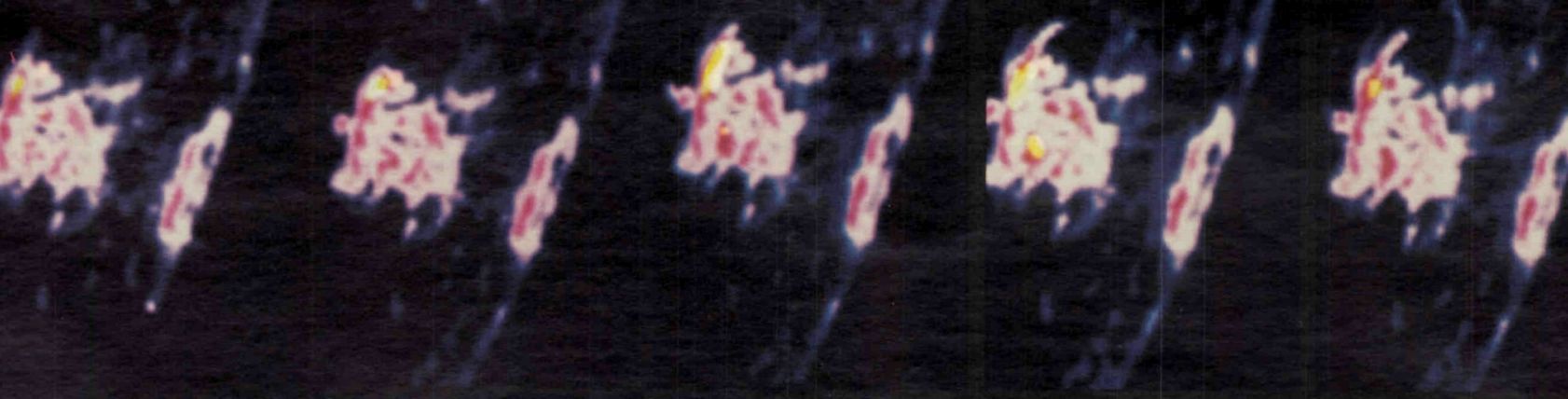
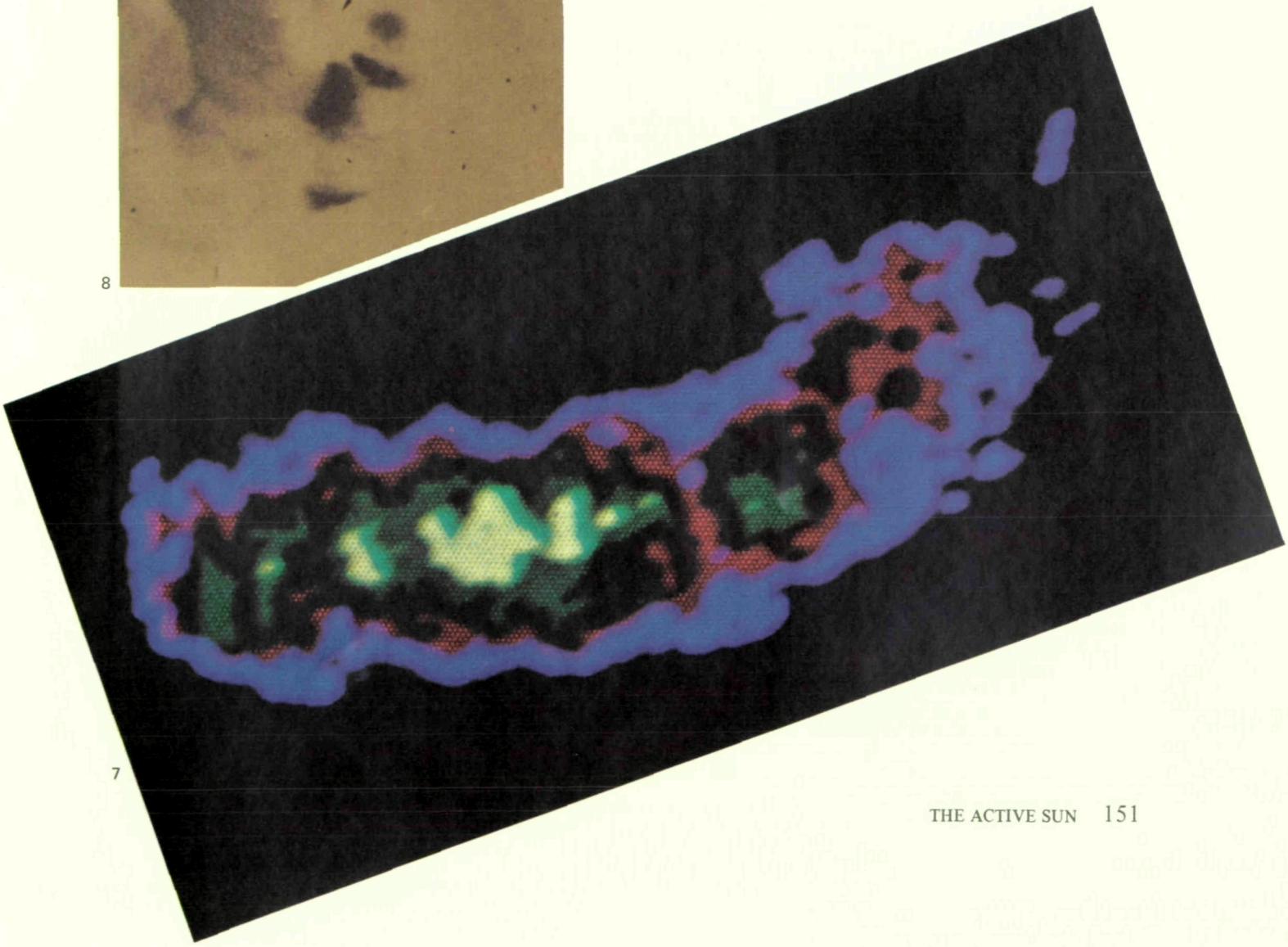


1 2 3 4 5

6 **A SOLAR FLARE** in an active region near the limb of the Sun flashes out and then fades in color-contoured pictures (1-6) made by Skylab in the ultraviolet. In a sequence (1-5) covering 23 min, the brightest features are colored yellow; each samples the transition region, at about 300 000 K, where flare brightening is accentuated. In (6) the same flare, at the same time as (4), is shown in a composite view: chromosphere (blue), transition region (green), and corona (red), where loops lace the flaring region. This flare burst out near midnight in the central United States, while American solar observatories were shut down for the night. Skylab, in continuous contact with solar observatories all over the world, operated in another realm, where days were roughly 60 min, and nights were half as long.

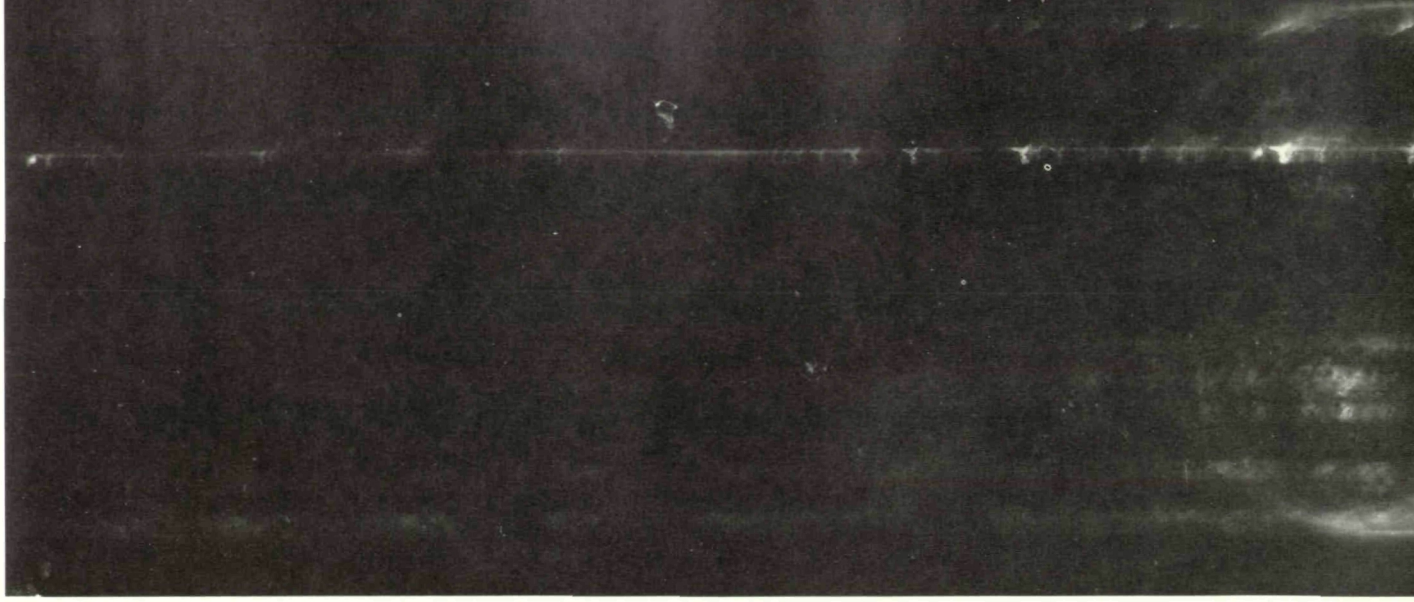
9

8



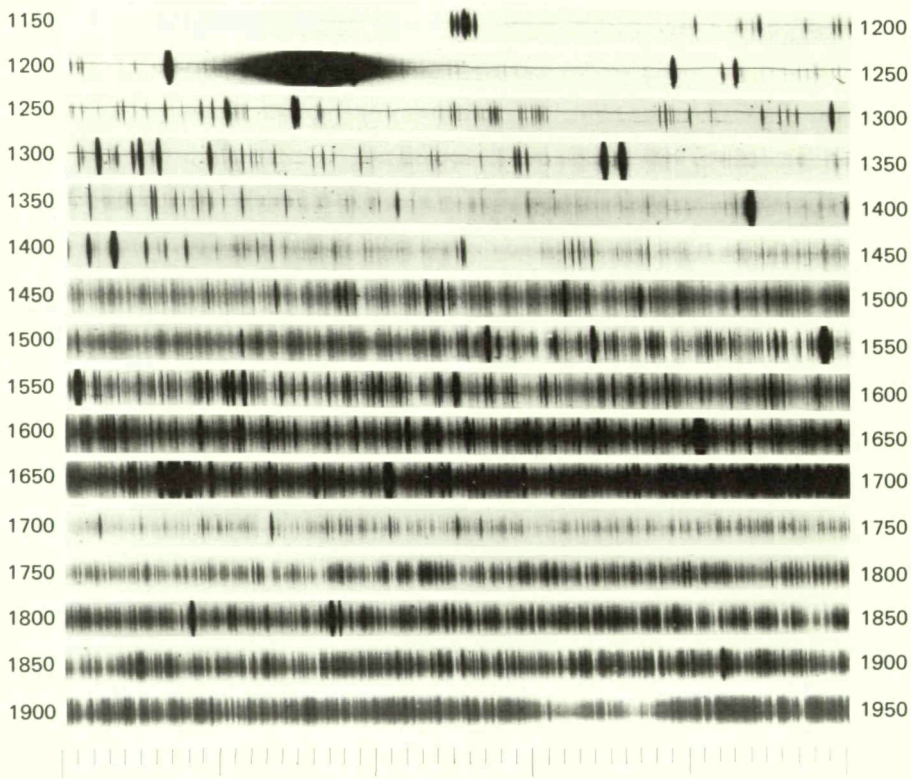
7

DURING A SKYLAB FLARE (7-9), magnetic loops in an arcade go off like a string of firecrackers as a wave of excitation sweeps along them, end to end. A color-contoured X-ray picture (7) shows the brightest areas yellow, fainter in green, red, and blue. We look down on the tops of about 10 green loops, strung out in a slightly curved arcade. As Skylab watched, the loops brightened one by one, flashing off and on several times—the most intense emission at their tops. An ultraviolet view of the same region (8), here printed as a negative, catches the brightening (black) of the right-hand end of the arcade about 6 min later. The flare occurred along the border of a sunspot, in the active region identified in the H_α picture (9).



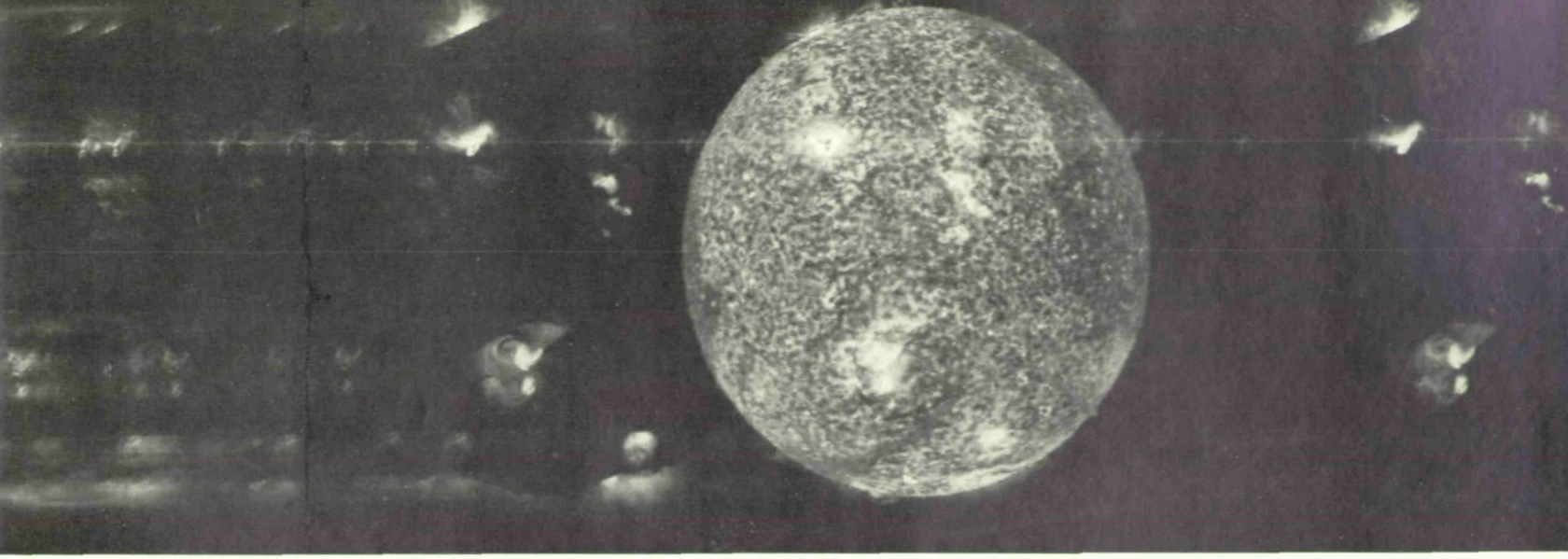
1

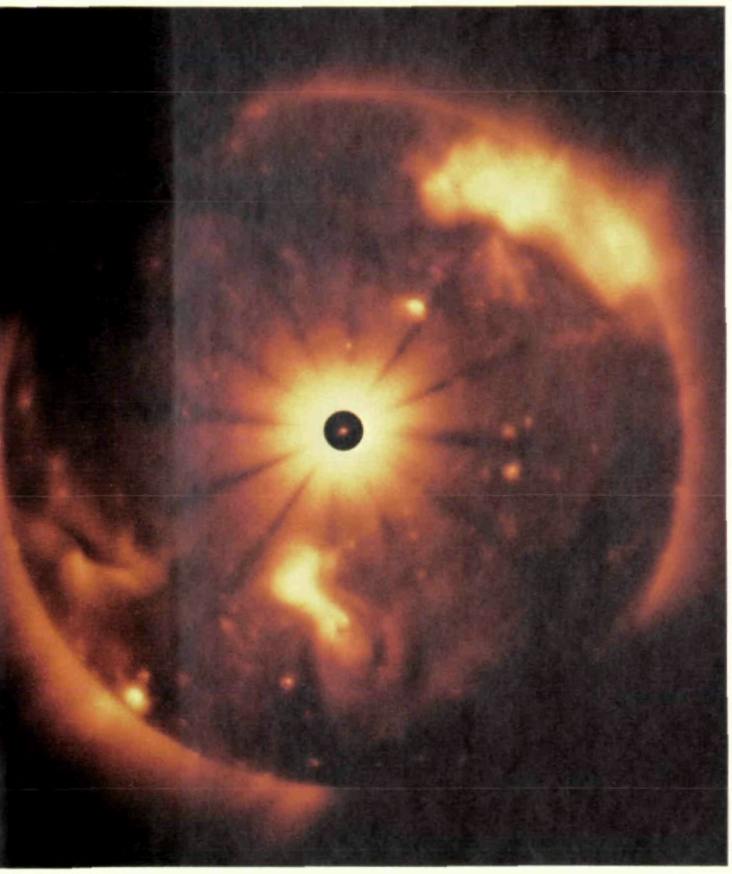
SPECTRAL IMAGES OF A FLARE are again spread out like a deck of cards in this ultraviolet spectrogram (1). The flare appears in the full-disk image of the chromosphere as a γ-shaped spot, so bright that it was reversed, or "solarized," on the original Skylab film. Images of the same flare appear at many other wavelengths in the nearly continuous streak of light that runs horizontally across this solar spectrum. At the extreme left we see the flare in light of iron vapor ionized 23 times, at temperatures of about 17×10^6 K, where it appears as a small cloud of emission. Images of other, nonflaring active regions on the Sun are also spread out, but are wholly absent in spectral lines that sample hottest temperatures. The unexpected but well-observed flare occurred late in the first Skylab mission, bringing cheer to a Skylab crew that was eager to observe one.



2

RICH PRIZES FROM SKYLAB'S SPECTROGRAPHS included detailed ultraviolet spectra of solar flares, such as (2), showing about 5000 spectral lines, each the unique signature of a specific element in the flaring region of the Sun. The scale at left gives the wavelength in angstroms. The identities and shapes of spectral lines—which appear as dark, vertical streaks in this negative print—contain encoded information on the physical conditions within the flare. The broad, lens-shaped line near the *top* is the strongest spectral line of hydrogen, most abundant of all elements in the Sun. To secure this spectrum, taken in the late stages of the same flare as shown in (1), Skylab astronauts aimed the massive telescope mount at the point of brightest flare emission with a precision that could split the thickness of a dime the length of a football field away.





3

WHERE A FLARE ERUPTS (3), the ultraviolet spectrum changes abruptly. Lines in the same, limited region of the solar ultraviolet spectrum are compared in (4) for the quiet Sun and in (5) during a Skylab flare. Both are negative prints: black, vertical spectral lines are really bright features of the solar spectrum. Four strong lines (due to ionized silicon and carbon) brighten and broaden dramatically during the flare; and many new bright spectral lines appear between them, as ultrahigh flare temperatures excite and ionize solar atoms in the vicinity of the flare.

4

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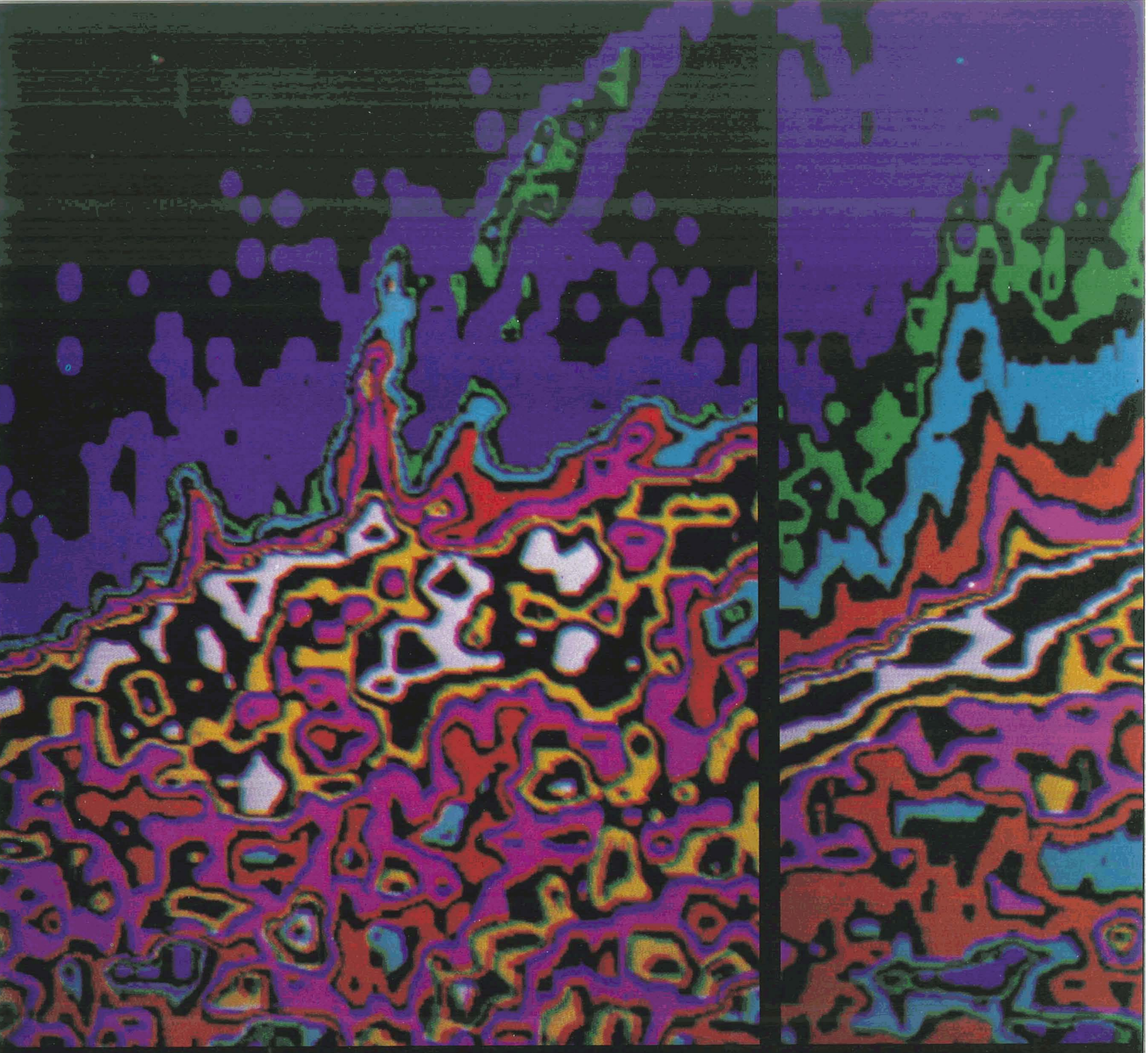


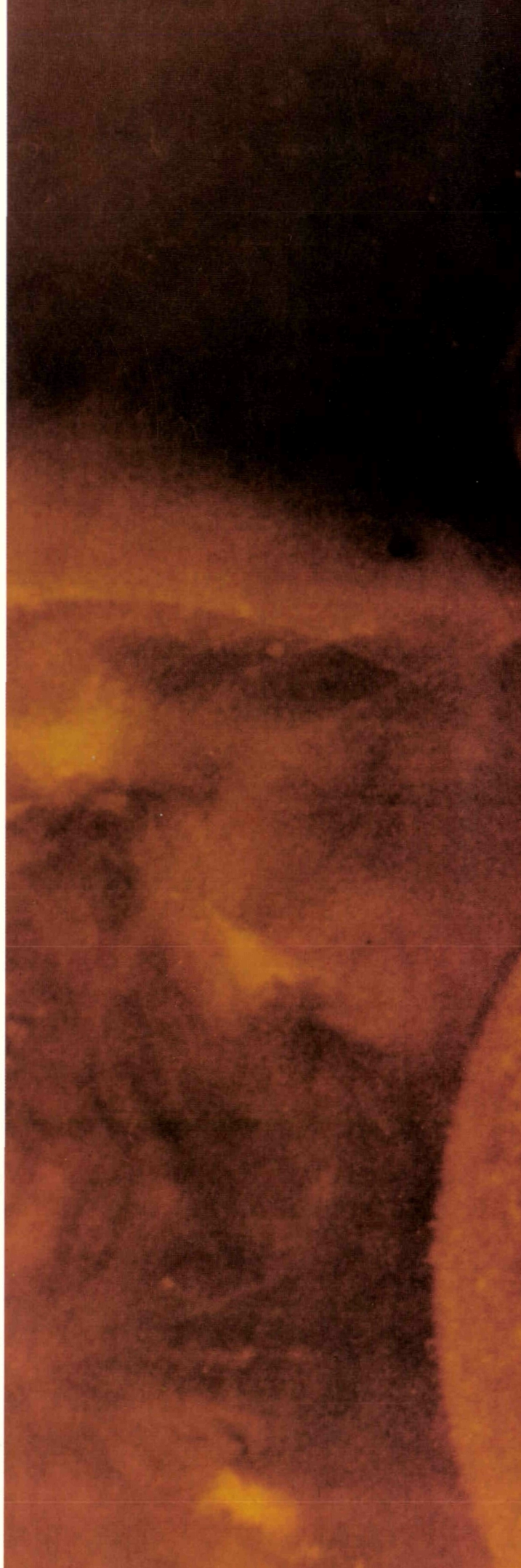
ACTIVE PROMINENCES

Solar prominences classified as "active" are those that suddenly erupt, often rising as though propelled outward through the corona by loaded springs. Others have been noted to mysteriously and quickly disappear, their giant forms suddenly erased from chromospheric pictures made in wavelengths visible from the ground. Combined ultraviolet and X-ray observations of active prominences by Skylab captured many of these dynamic features of the Sun, and recorded the details of their eruption and disappearance, and the apparent magnetic origin of their expulsion. Clearly visible in the ultraviolet dissections of giant, eruptive

prominences were the twisted sinews of magnetic force that tore them from the Sun. Prominences that vanished in ultraviolet wavelengths that sampled cooler temperatures in the solar atmosphere were followed as they appeared in other wavelengths, exposing the secrets of their apparent vanishing act. The persistent coverage of Skylab's ultraviolet telescopes caught and followed the details of some of the largest and most dynamic prominence eruptions that have ever been seen on the Sun, and documented their association as triggers for other, even larger eruptions in the outer corona. Concurrent observations from Skylab's unique battery of solar telescopes provided an almost immediate understanding of the largest explosive prominence yet seen on the Sun.

SOME OF THE PROMINENCES that float like lazy clouds above the solar surface suddenly erupt and break away from the Sun in cataclysmic action. Much larger than flares, and not always associated with them, eruptive prominences constitute some of the Sun's most spectacular sights.

The "elbow prominence" was accidentally photographed by Astronaut Garriott while observing a small flare near the limb of the Sun beneath the mighty arch. We see it here in ultraviolet light of ionized helium, which tells us that its temperature was in the range of 30 000 to 90 000 K—far cooler and denser than the million-Kelvin corona through which we see it pass. Its intricate form traces out twisting magnetic field lines as they are torn from their roots in the chromosphere. The eruption began as a low-lying prominence that soared upward; here, after about 20 min, it has reached a dizzying altitude of more than 600 000 km above the Sun—almost twice the distance that separates Earth and the Moon. Our planet, for scale, is smaller than the black dot near the limb of the Sun beneath the arch.



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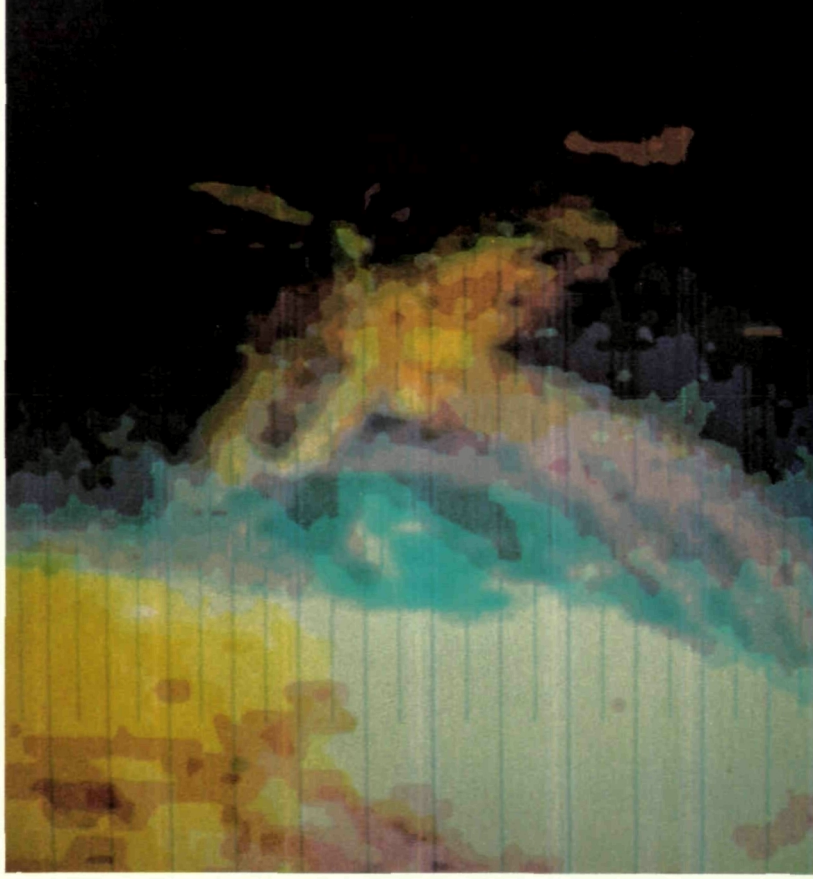

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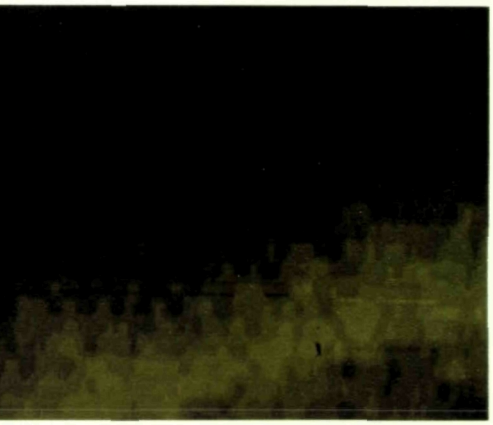

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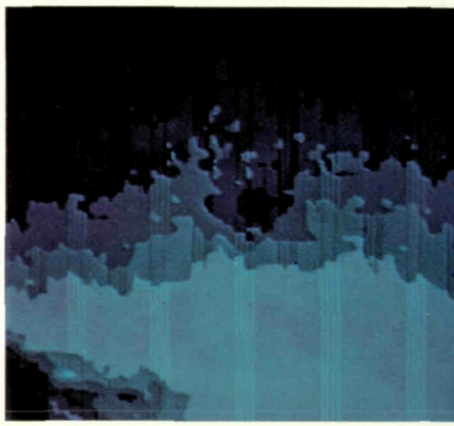

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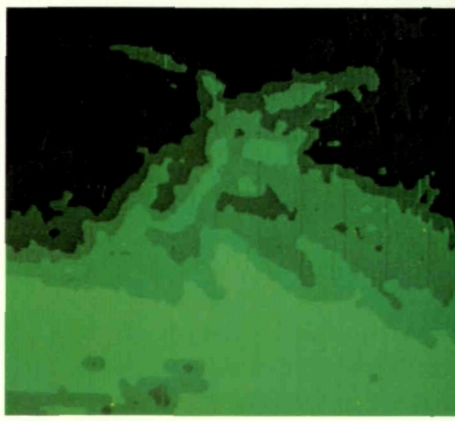

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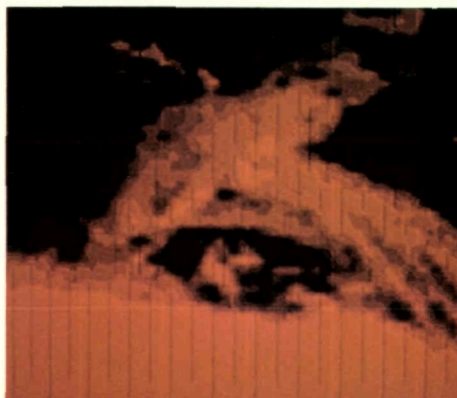
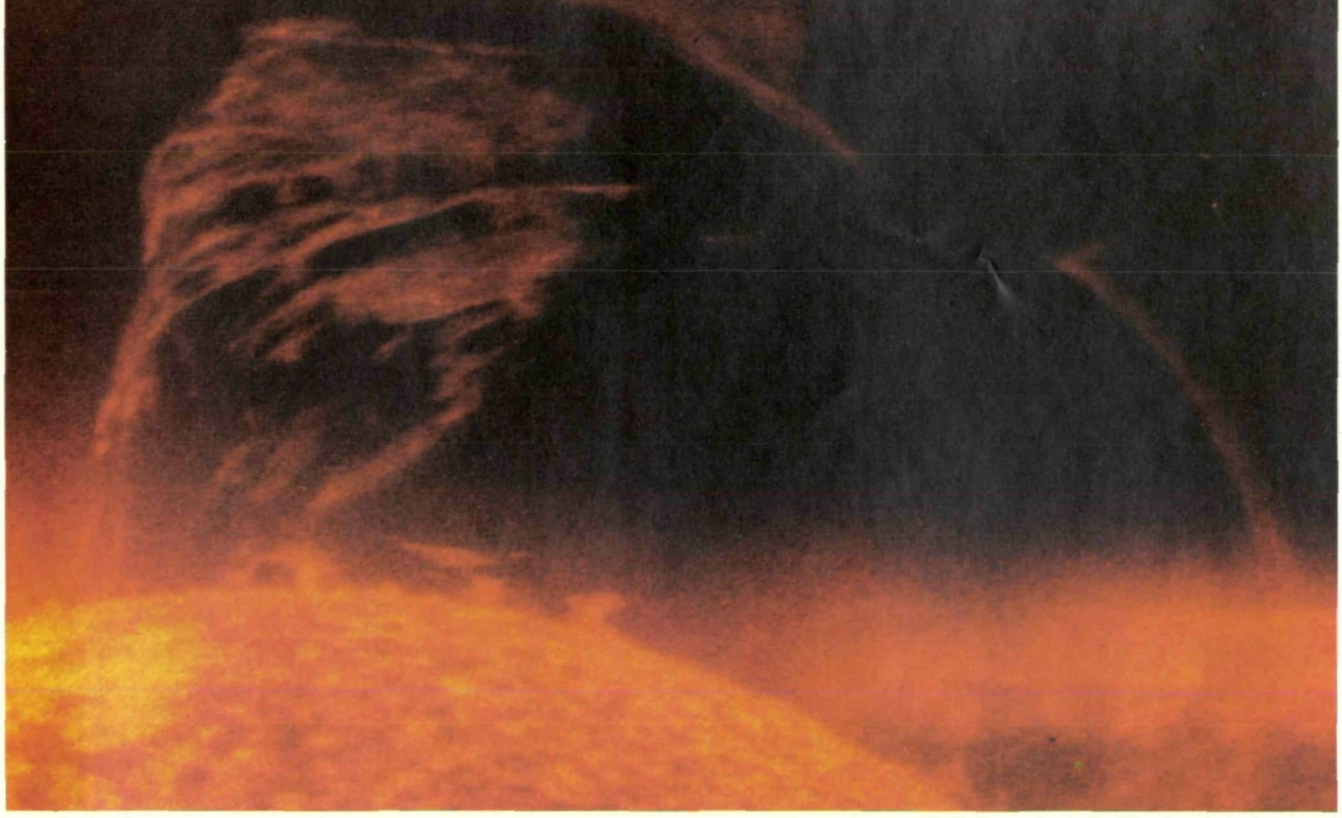


SKYLAB TAKES THE TEMPERATURES of two active prominences by observing them in different ultraviolet spectral lines, here distinguished in color code. In each case they prove to be extensions of the cooler chromosphere into the hot corona.

(1,2,3) are color-coded dissections of the active prominence shown in composite form in (4), which is a feature seen edge-on above the solar limb. The active prominence is made of material mostly at chromospheric (red) temperatures, with some hot strands (blue) at about 150 000 K. At coronal temperatures (green) it is too cool to be seen.

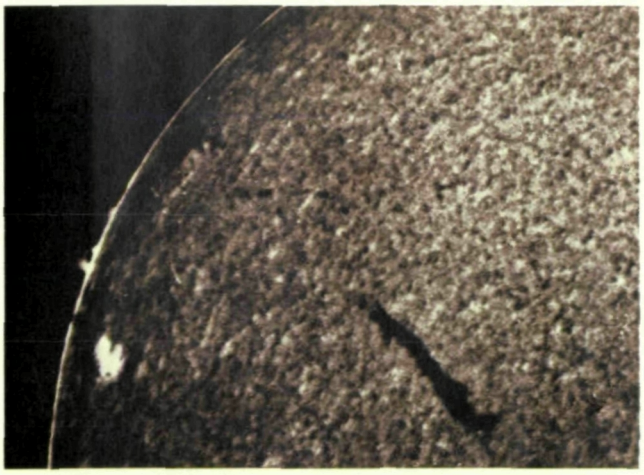
A more active prominence (5-8) seems made of chromospheric (red) material in twisted strands, with an outer (green) sheath at 150 000 K. In the corona (blue), it almost disappears; in (8) the three color-coded views are combined.



9

THE SUN ENJOYS A MIDNIGHT FLING, casting off 6 billion metric tons of filmy outer dress at speeds of more than 100 km/s. This immense eruption (9), arching here more than 300 000 km above the Sun, was caught in Skylab's ultraviolet eye just before midnight, Houston time, about 10 min after it had left the surface of the Sun. Pushing coronal material ahead of it, the eruption produced an even larger transient disturbance in the outer corona, and eventually dissipated in interplanetary space. Here, in light of ionized helium, at temperatures of 30 000 to 90 000 K, we see its clearly twisted form—revealing the coiled, magnetic springs that tell the secret of its expulsion from the Sun.

(10-13) THE SUN ERASES A PROMINENCE in the chromosphere, only to see it reappear in the X-ray corona. Between H_α chromospheric pictures (10) and (11), 14 hr apart, the prominence (which appears on the disk of the Sun as a dark, black filament) disappears. A Skylab X-ray view of the corona (12), made about the same time as (10), reveals a dark cavity above the filament, like a small coronal hole cut to fit the prominence below it. After the filament disappears from the chromosphere, the X-ray cavity fills in with hot, bright material (13), suggesting that the prominence has ascended, heating up drastically as it goes. Disappearing filaments have long been noted in H_α in the chromosphere; X-ray pictures of the upper solar atmosphere illustrate that what disappears at one level may reappear at another.



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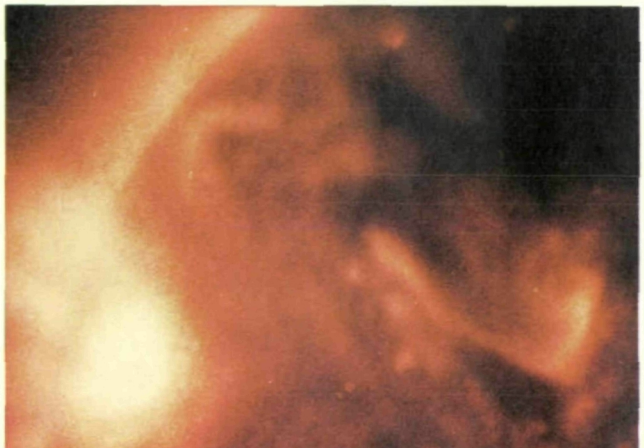
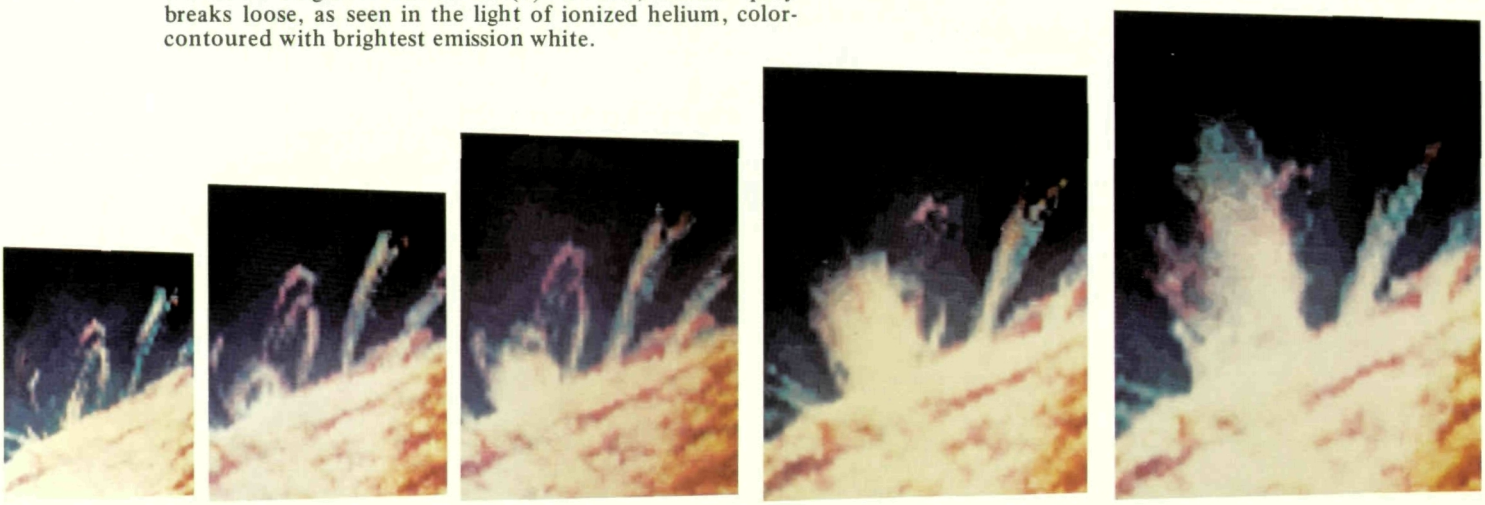


13

BREAKING THE GRIP of the closed magnetic loops that constrain other gases around it, a spray of chromospheric material surges upward, free of the Sun. An ultraviolet sequence (1-5) depicts action in pictures made about 5 min apart, each a composite of separate images made in chromospheric (red), transition region (green), and coronal (blue) temperatures. Eruption begins (2) as material in or near a small, compact loop develops enough energy to overcome the Sun's magnetic bonds. In (6) another, similar spray breaks loose, as seen in the light of ionized helium, color-contoured with brightest emission white.



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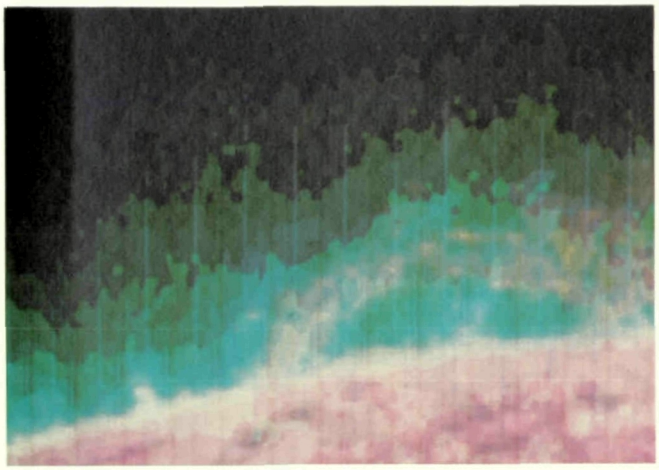
AN ACTIVE PROMINENCE (7,8) printed in colors to represent different temperatures, alters its appearance in 3 hr, while Skylab circled twice around Earth. Later the same prominence erupted, vanished, and subsequently reformed, filling the arched magnetic lines with new material from the chromosphere.

(9-13) COLOR COMPUTER PROCESSING of Skylab ultraviolet images differentiates subtle changes in a wispy prominence arch. In wavelength-composite pictures (9,10), little change is apparent over a 34-min period. The same scene, when shown as time differences in each of three separate wavelengths (11-13), reveals that during this time the cooler regions (11) are changing, while hotter ones (12,13) are not. In each of these three views, made at chromospheric, transition region, and coronal temperatures, the earlier picture was colored red and the latter, green. Yellow, their sum, signals regions of no change. In this case the corona (13) seems to care little about what goes on at lower temperatures within it, and at transition region temperatures (12) the effects are also slight. With the layer of change identified, another primary color, blue, is added to the chromospheric view in (14), to introduce a third, intermediate time: Blue is 17 min later than green, which is 17 min later than red. Their sum, where no change occurs, is white.



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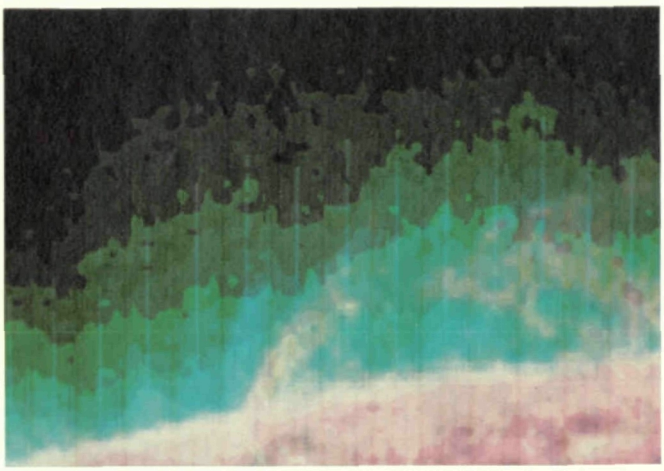

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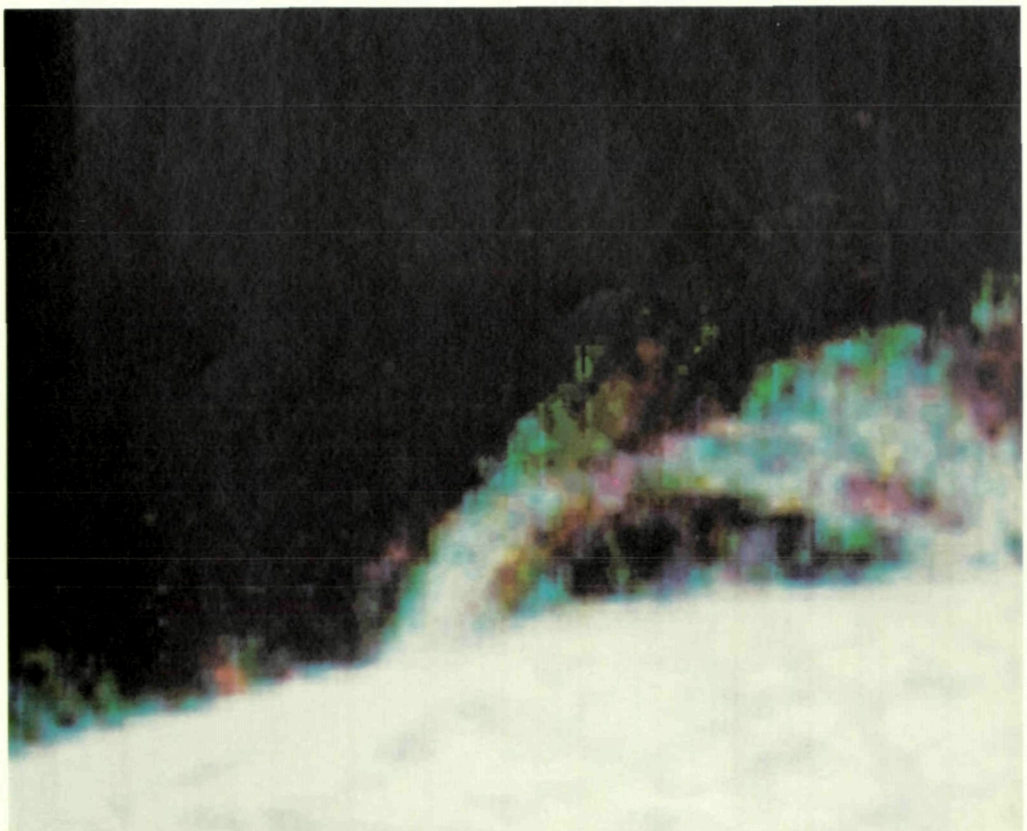

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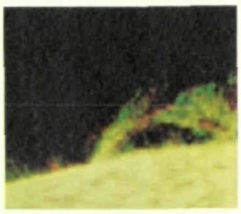

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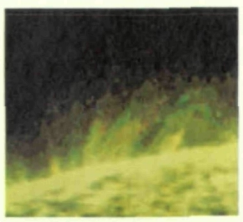
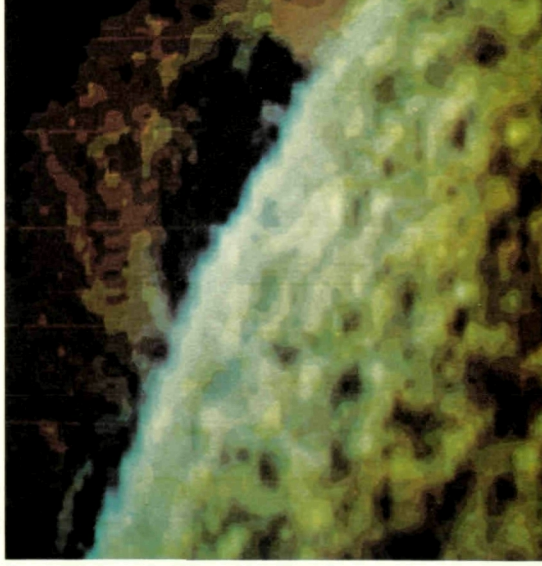


13

A GIANT PROMINENCE (5), one of the largest seen in a decade, lifts off from the Sun. Sequence (1-4) recorded the imminent eruption for over an hour, but little change occurred. Each picture is a color composite of separate ultraviolet views that isolate different temperature layers. The three contained in (1) are stacked below (2); the hottest is blue and the coldest, red. Invisible at coronal temperatures (8), the prominence is mostly 20 000 K material (6), with hotter strands at about 70 000 K in green (7), which hint of twisted sinews of magnetic force. In (5), taken half an hour after (4), the prominence erupts and is caught in Skylab's net. In (9), taken later, a rain of prominence material falls back on the area of the solar limb where the prominence once stood.



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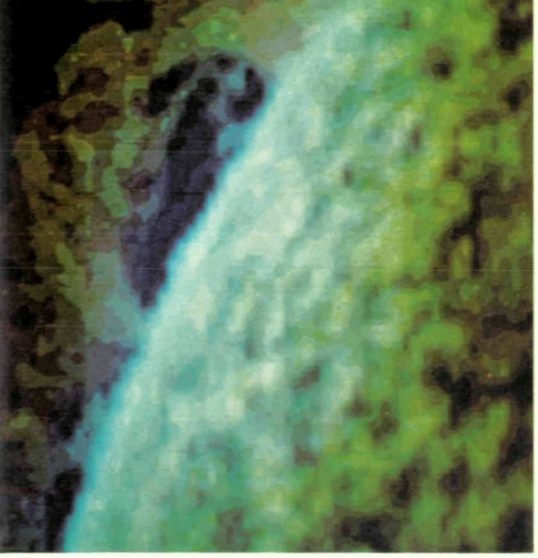

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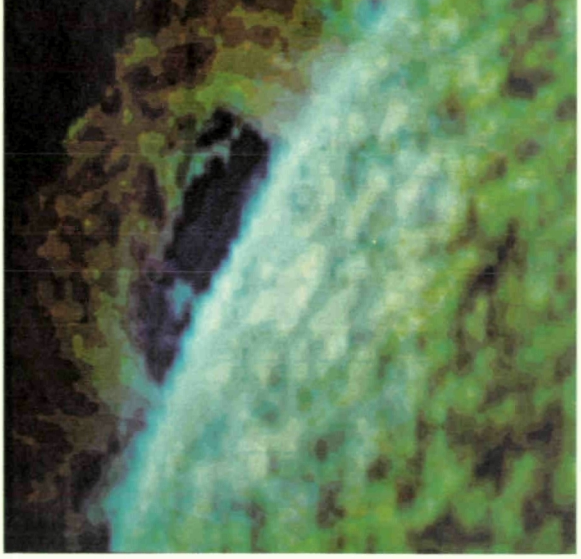

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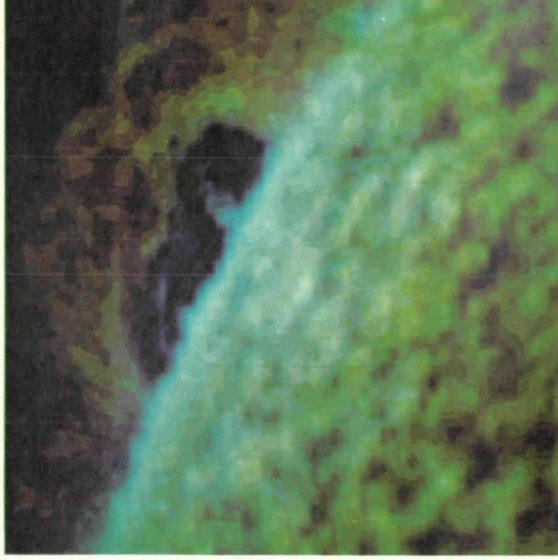

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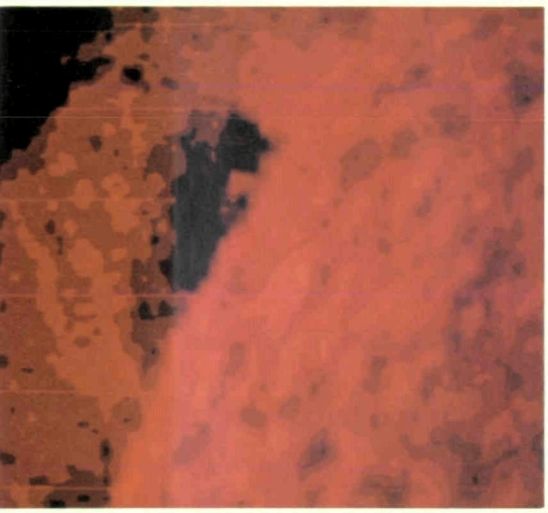

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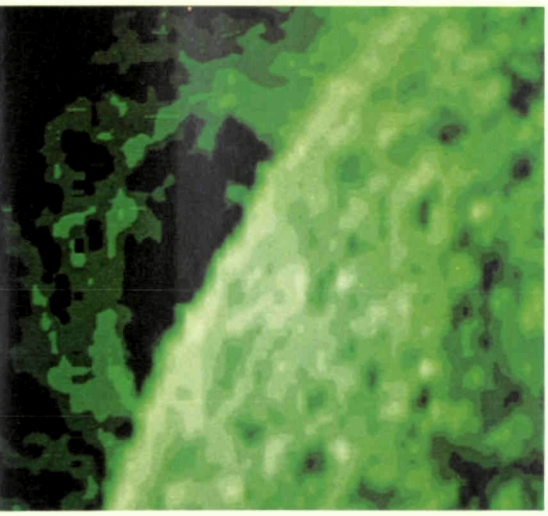

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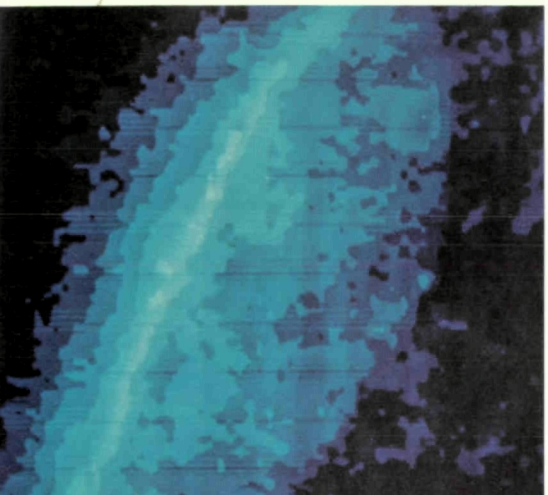

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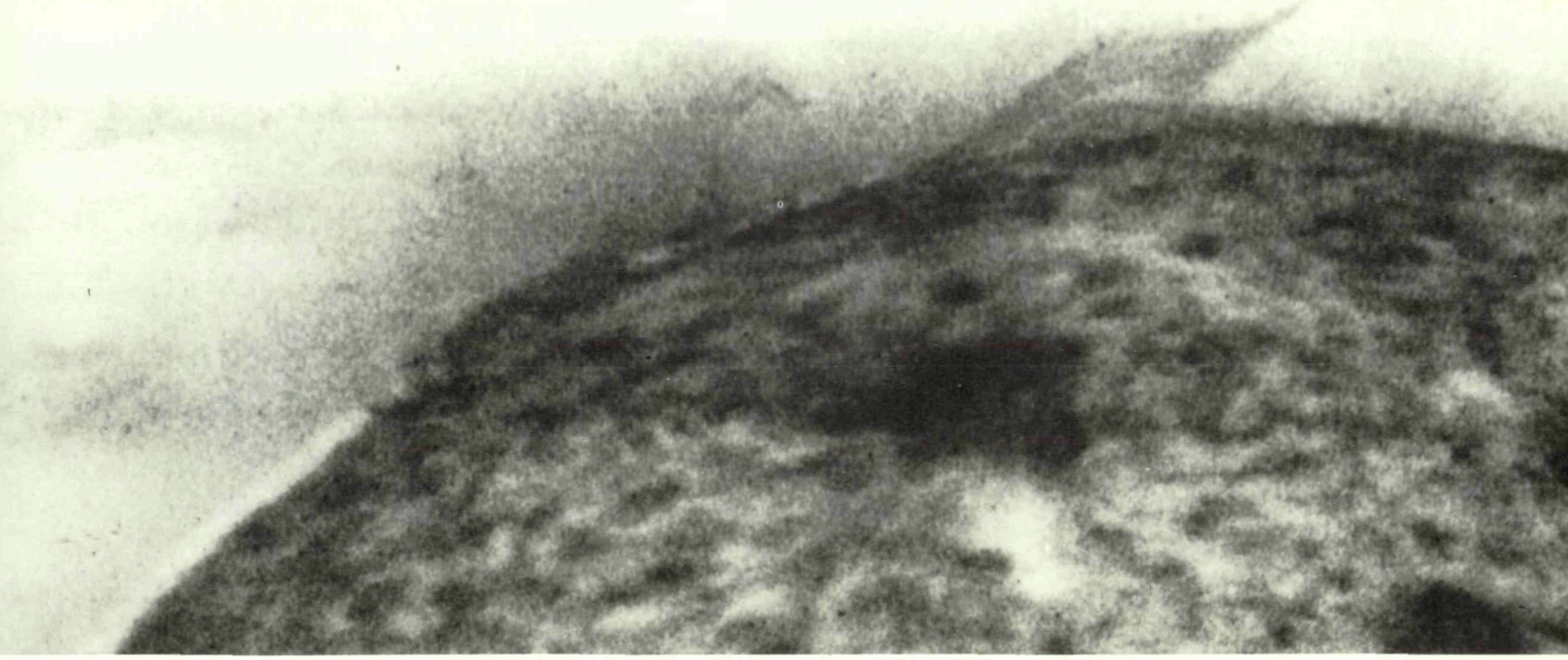

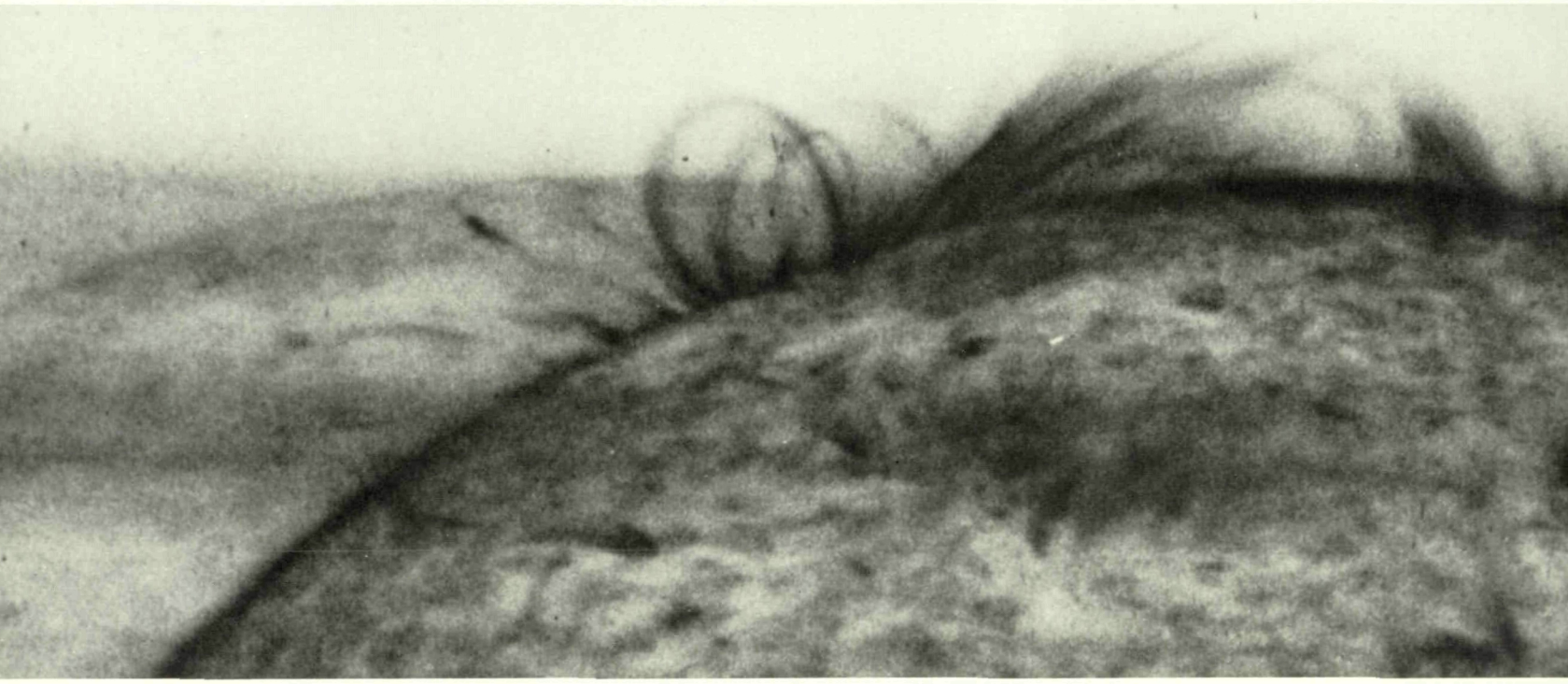

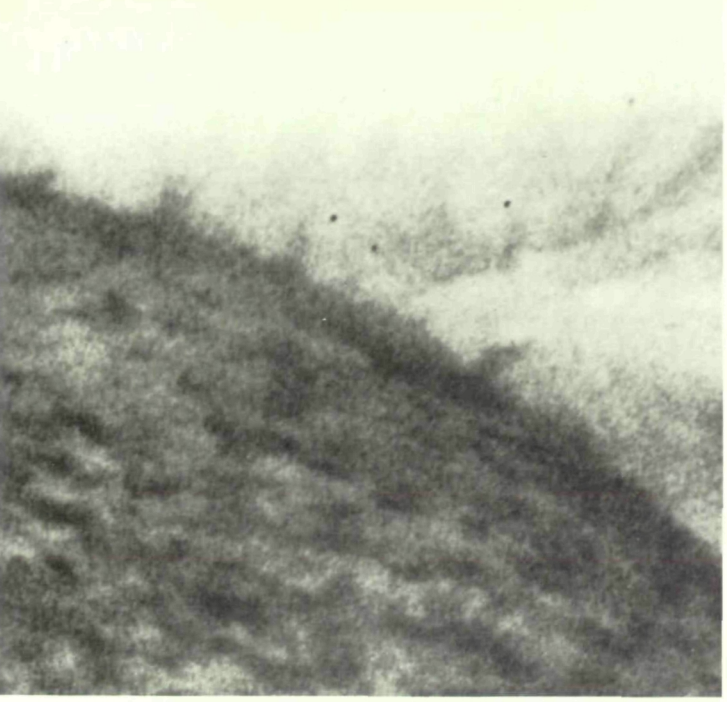

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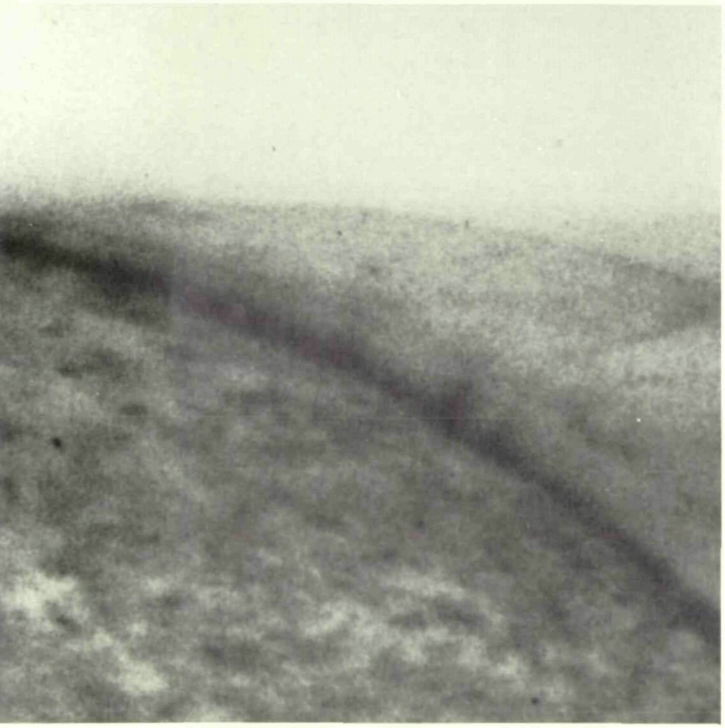
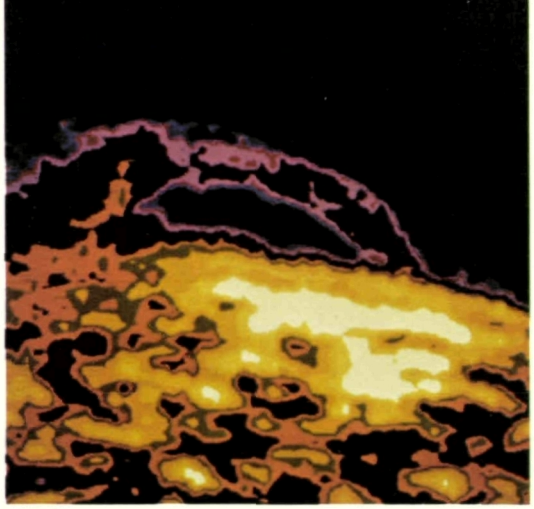
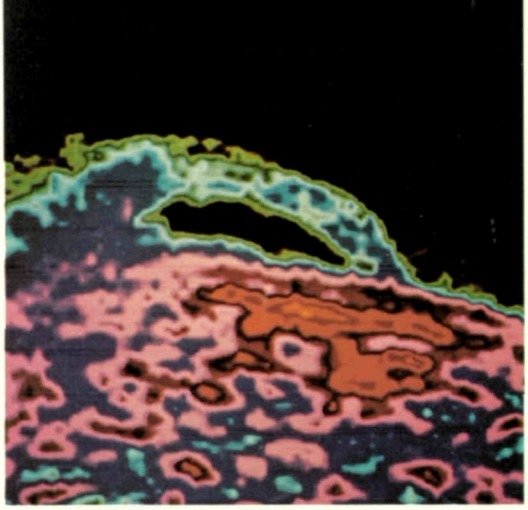


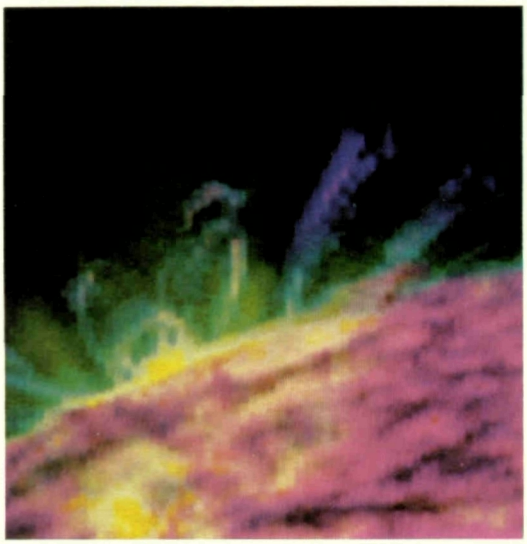
2

3

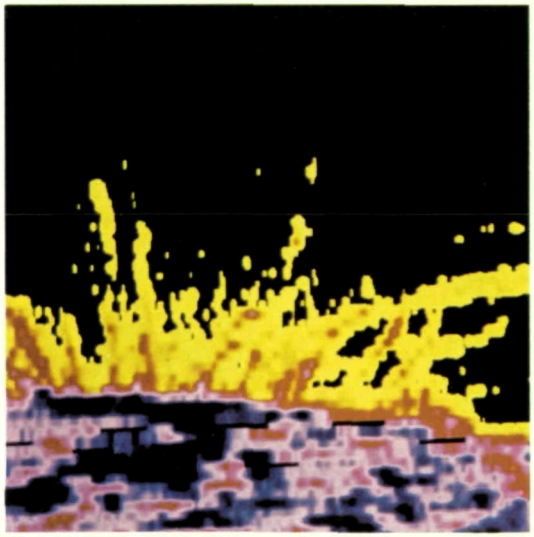
WITH STEADY HAND, a Skylab ultraviolet telescope dissects a prominence eruption as it leaves an active limb of the Sun. All three pictures (1-3) show the same region at the same instant. At chromospheric temperatures (1), the prominence stands out like a sharp-nosed rocket poised to leave the solar surface. Magnetic field lines that channel its flight are far better seen in (2), where material at transition region temperatures of about 600 000 K outline fine loops that soar from place to place on the solar limb. At coronal temperatures of about $2\frac{1}{2} \times 10^6$ K (3), the prominence is lost in searing clouds of hot iron vapor, where it is far too cool to be seen.

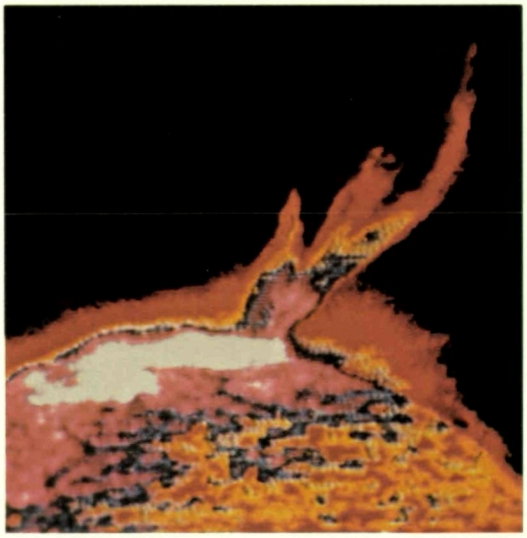


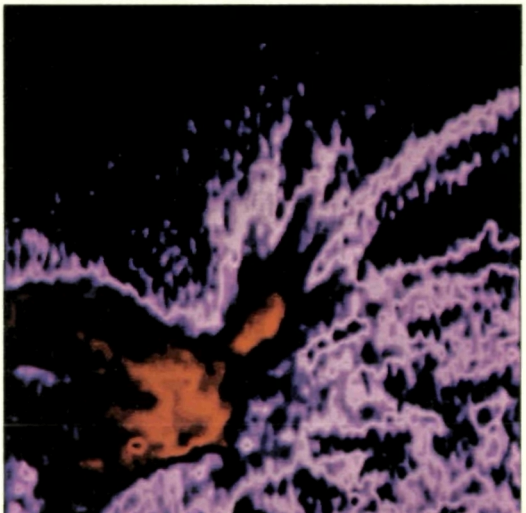


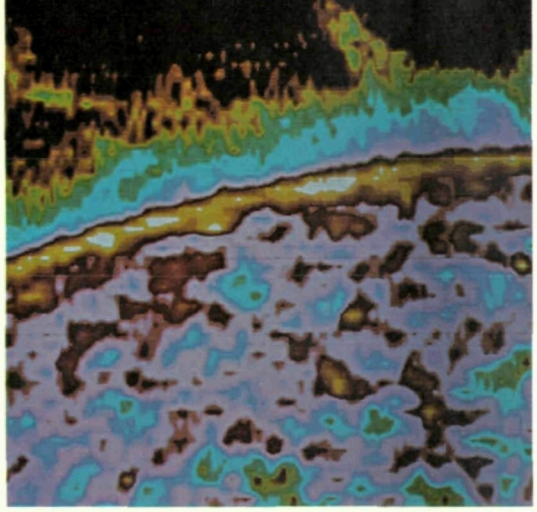
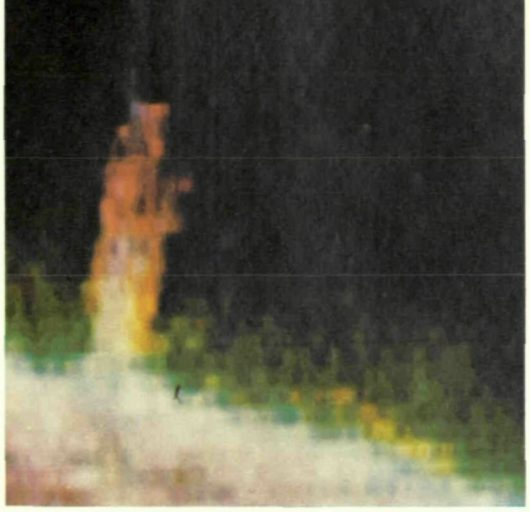
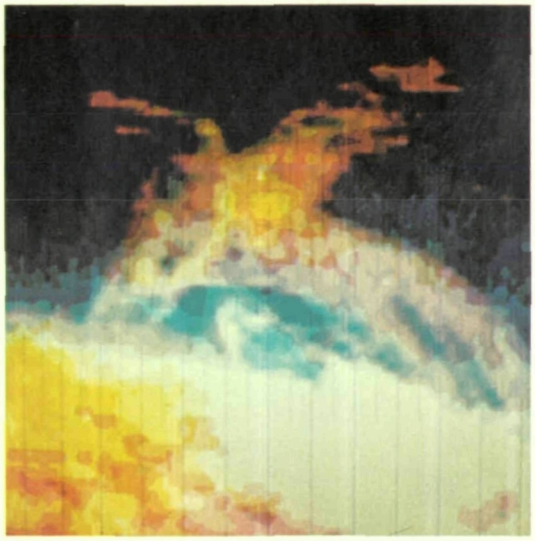
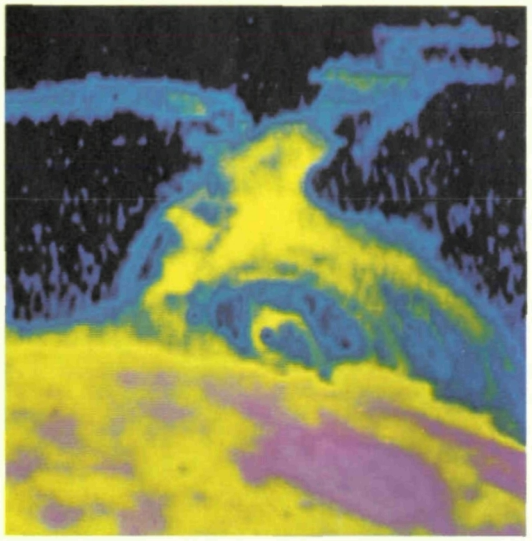
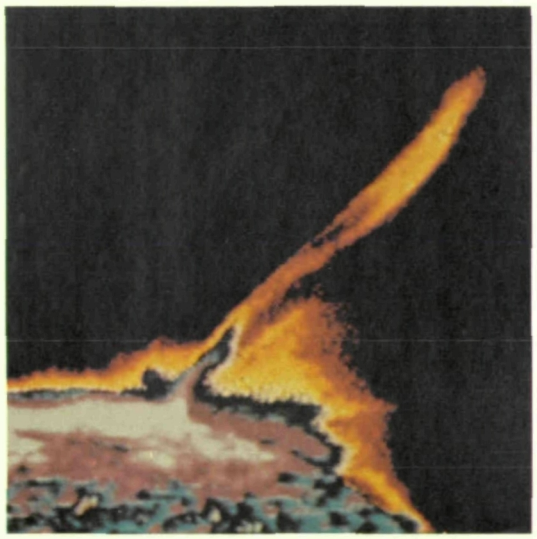
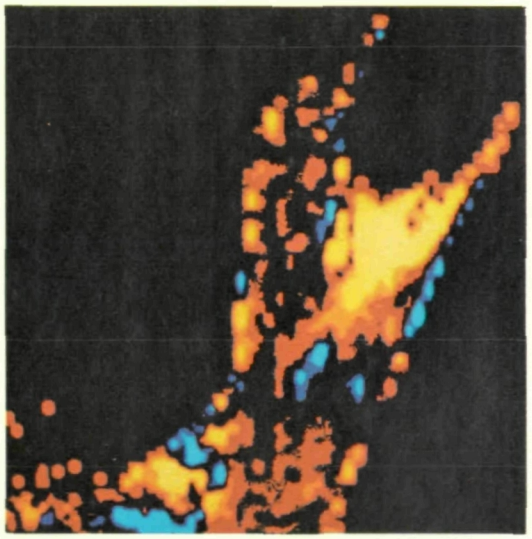
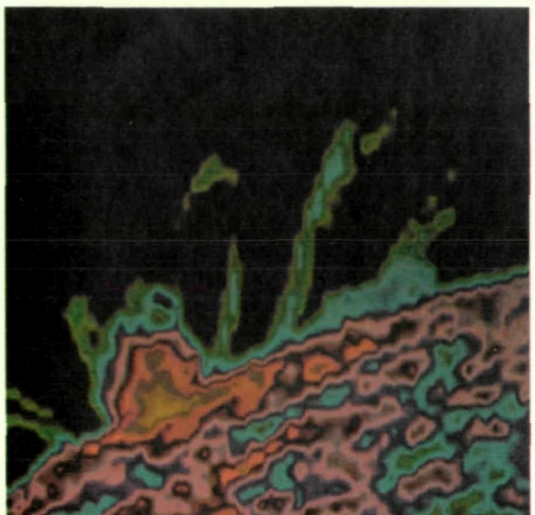
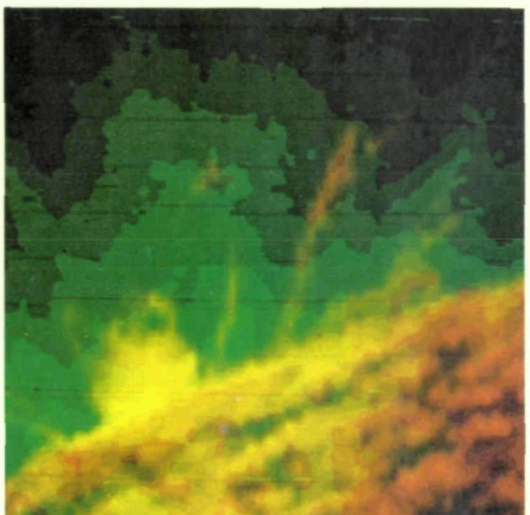


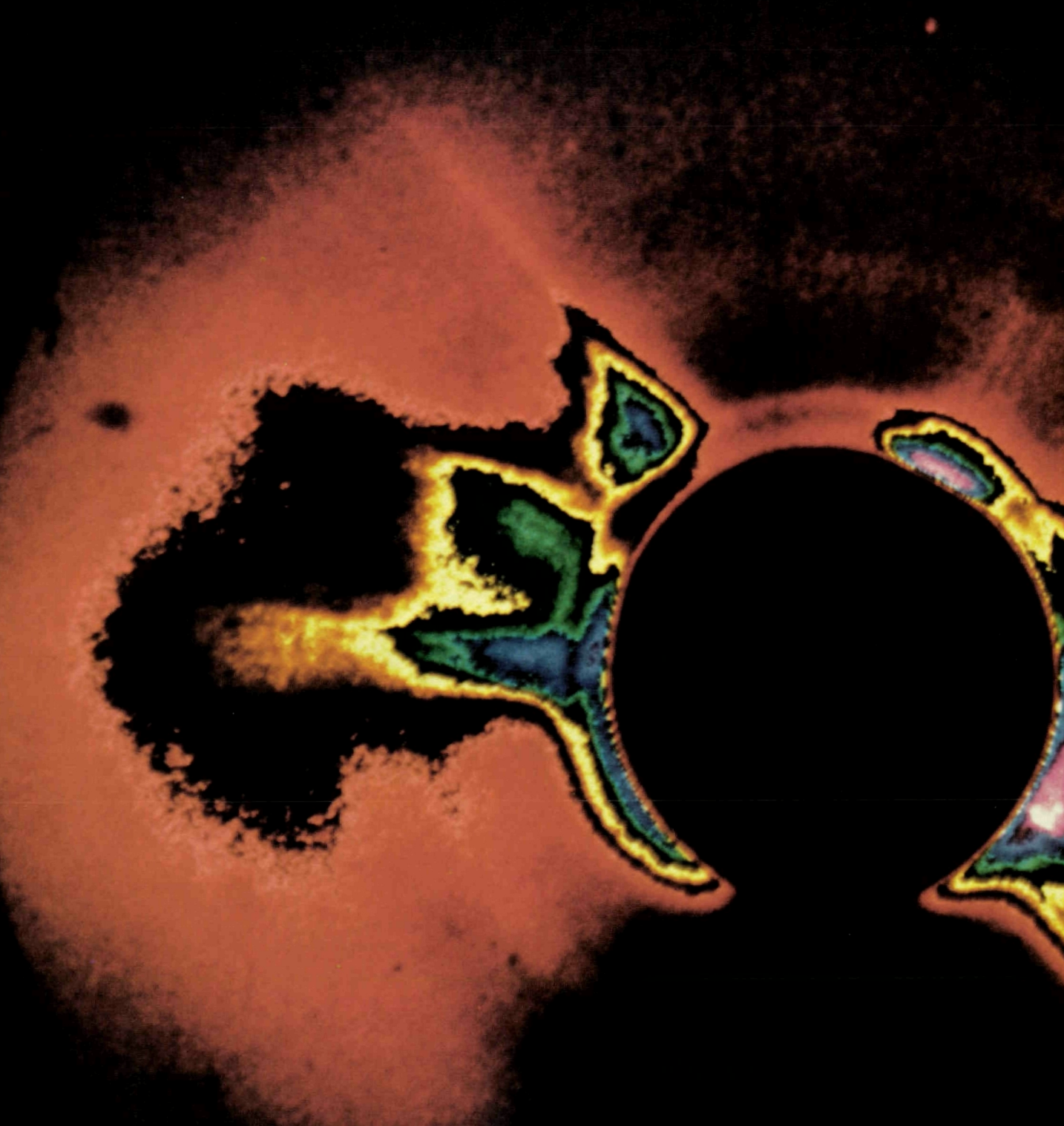
SOLAR PROMINENCES IN ACTION: These are some of Skylab's many-splendored views. Interpretation of the rich store of Skylab ultraviolet solar data was facilitated by computerized color enhancement of the original black-and-white images, highlighting subtle but important brightness differences. Color enhancement of solar data was among the new techniques of data reduction brought into use by Skylab scientists.





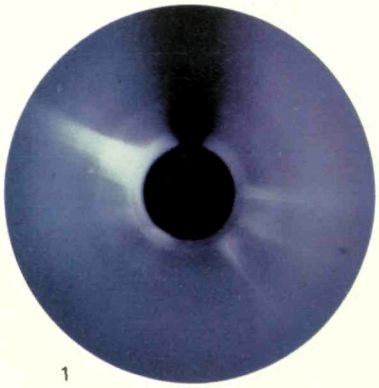




CORONAL TRANSIENTS: THE EXTRAVAGANT SUN

As though held back through all the years, the Sun released for Skylab's view a shower of surprises in the outer corona in scale and numbers wholly unexpected. Indications of large, transient disturbances traveling through the Sun's outer corona had been noted in solar radio records and found in coronagraph observations from earlier, unmanned spacecraft, but never had man seen these gargantuan loops rushing outward at fantastic speeds with the sharp detail of Skylab's coronagraph coverage. When the first was seen, early in the first manned mission, astronomers were elated to have captured an event of such surprising proportions: detailed pictures of the expulsion from the Sun of an eruption bigger than the disk of the Sun. Then, more and more were seen until, at the end of Skylab's life, more than 100 had been recorded. They now loom as our Sun's biggest and most dynamic intrusions into the world of interplanetary space, and a major reason for reassessing our picture of activity on the Sun. Because of Skylab's extensive, concurrent coverage in ultraviolet and X-ray wavelengths, discovery was followed, in subsequent analysis, by a full description of the features and causes of coronal transient disturbances. Their numbers clearly followed the state of activity on the Sun, increasing in frequency as sunspot numbers rose. It was clear that some of the coronal transients were initiated lower in the solar atmosphere by flares; another, larger class was associated with prominence eruptions. More than three-fourths of the observed coronal transients originated in coronal active regions and more than 70 percent were initiated by eruptive prominences that acted as triggers to set off and propel the giant coronal loops. Flares that were accompanied by mass ejections were always followed by coronal transients. They contained too much material to be simply expanding prominences, but were recognized as a coronal phenomenon: large pieces of the outer corona, pushed outward at speeds of 100 km/s to more than 1200 km/s, drastically altering the corona's outer form. Though truly immense and much larger than prominences, coronal transients contain very little solar matter, and carry away but a negligible part of the Sun's total mass. Perhaps most important, they were found to be associated with a class of disturbances in the solar wind, demonstrating that they were propelled at least as far as the orbit of Earth to make their imprint on the upper atmosphere of our planet, 150×10^6 km away. Larger coronal transients have now been identified as one of the previously missing links by which part of the explosive energy of solar flares is carried to Earth, where it disrupts the ionosphere and geomagnetic field, with significant impact on our everyday life.



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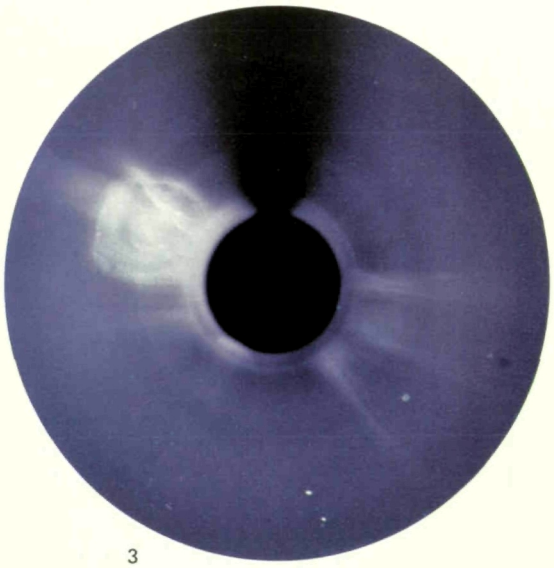

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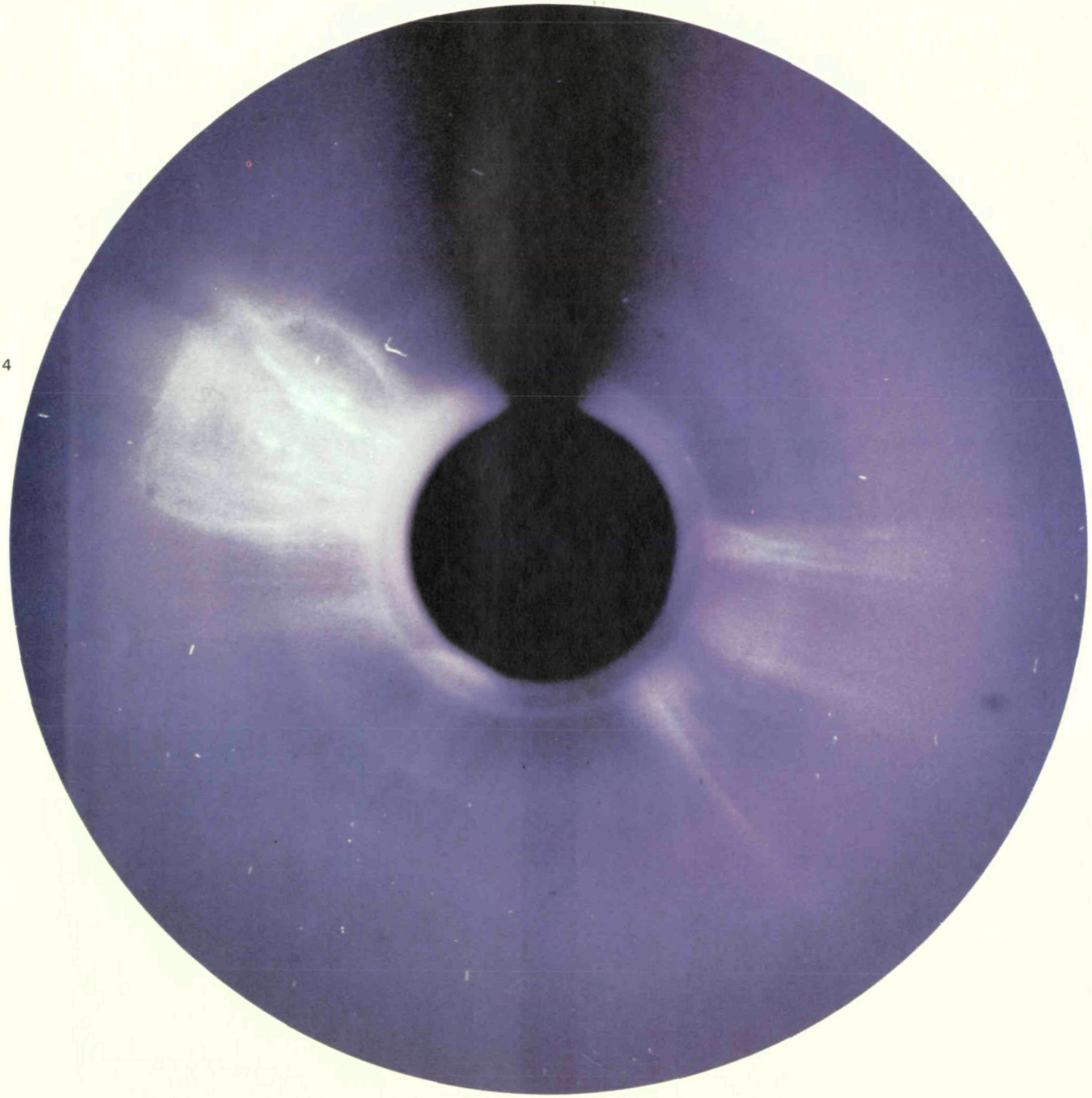
SKYLAB CAPTURES a gargantuan disruption in the corona as it develops and moves outward from the Sun (1-4). Rapid picture rates were needed to catch its movement. Sequence (2-4) covers a period of but 23 min, during which time the outer shell of the disturbance traveled nearly a million kilometers. An hour before, in (1), the corona gave little hint of the action that was to come.

The trigger of this coronal transient, like many others seen by Skylab's coronagraph, was an eruptive prominence that surged outward from the limb of the Sun, ejecting matter that disturbed the outer corona. We see the surge in action in (5), in ultraviolet light of ionized helium. Simultaneous observations like this made possible an almost immediate understanding of the new-found cosmic phenomenon.

4



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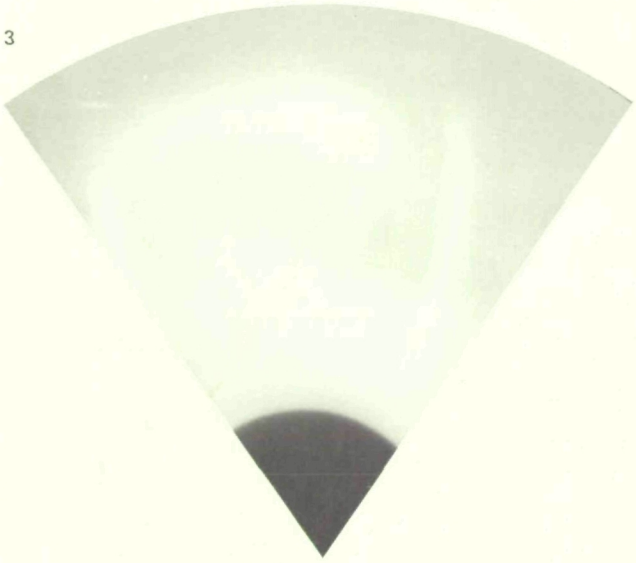

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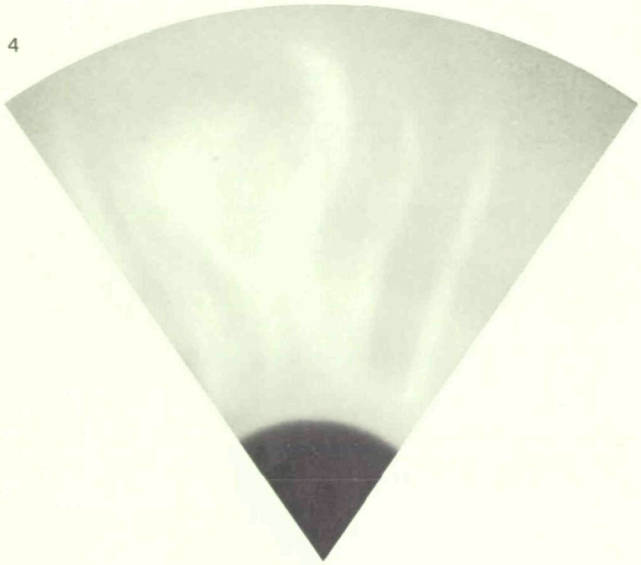
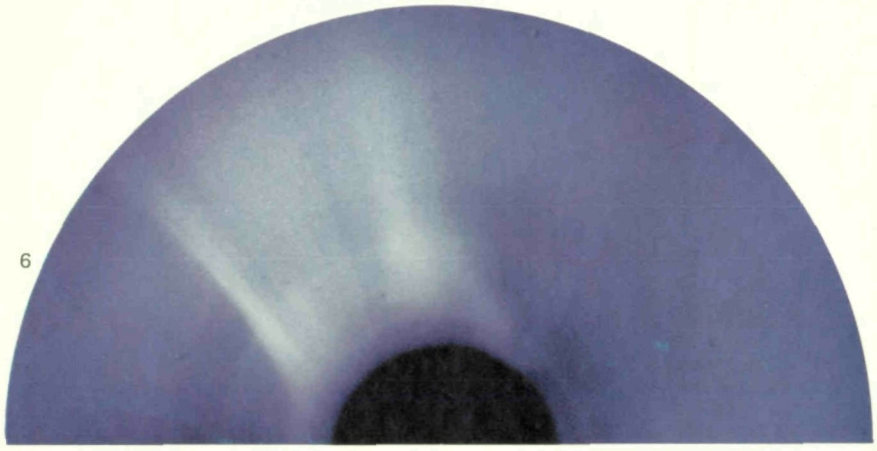


ANOTHER CORONAL BUBBLE is blown outward from behind the oversize occulting disk that hides the Sun. In but half an hour it exceeds in size its parent star—and still it grows, expanding outward in the void of space. Sequence (1-4) covers 89 min, about the time for Skylab to circle once around the Earth—a world insignificant on the scale of these largest known solar features. In (5), outlines of the moving transient are shown for the times of (1-4), with a corresponding X-ray image of the Sun for scale. Although coronal transients are immense, they are mostly empty space—diffuse clouds of electrons and other atomic particles that represent but a negligible part of the Sun. A trillion coronal bubbles would weigh no more than our solid Earth. Had the Sun expended one of these transient features each day since it was born, the material lost would still be an insignificant part of the total mass of the Sun.

A CORONAL TRANSIENT of another kind blows apart nearly half the corona in these views (6,7) taken less than 2 hr apart. Skylab found that transient disturbances passing through the outer solar corona often rearranged the entire configuration of magnetic lines and loops that define coronal forms.

6



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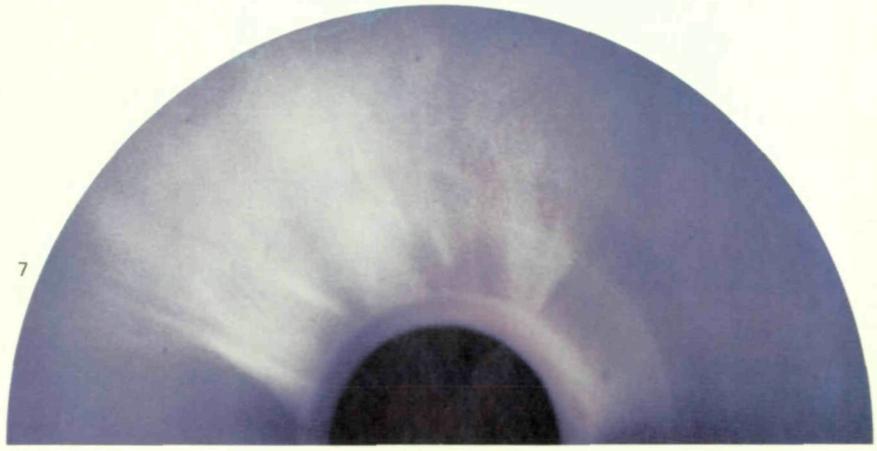
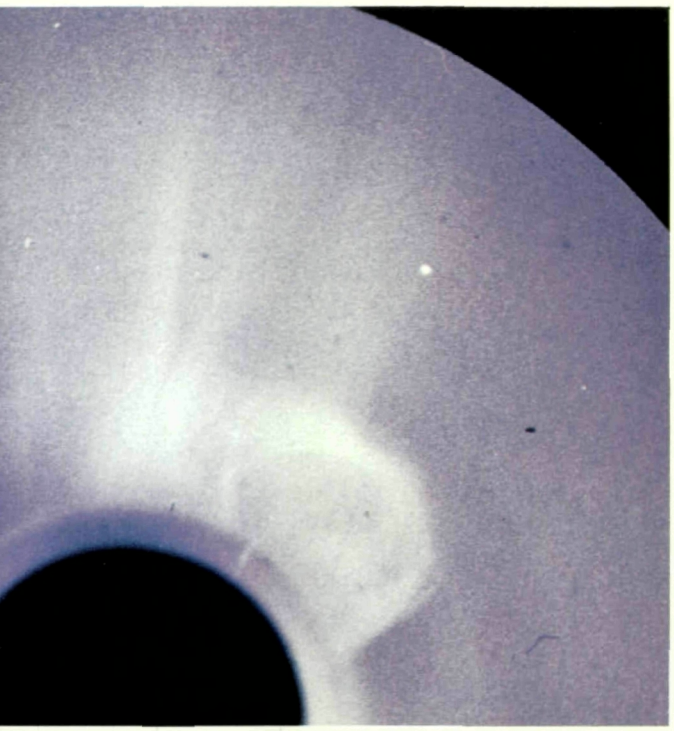


A COLOSSAL CORONAL TRANSIENT balloons outward from the Sun, dwarfing the disk of the Sun and the surge in the chromosphere that started it. Sequence (1-3) covers only 29 min. In (3) a simultaneous image of the ultraviolet Sun is superposed, revealing the eruptive prominence that lashes out like a tongue of fire propelling the great disturbance. The eruptive prominence was well observed from the ground in H_α. In (4), colored outlines trace the initial stages of the H_α eruption at times of 1 hr (green), 47 min (red), and 36 min (blue) before (1). A contour map of hard X-ray emission from the low corona over the disturbance on the limb is shown in (5), for time midway between (1) and (2). Brightest X-ray emission comes from regions of the corona where the local temperature exceeds 3×10^6 K.



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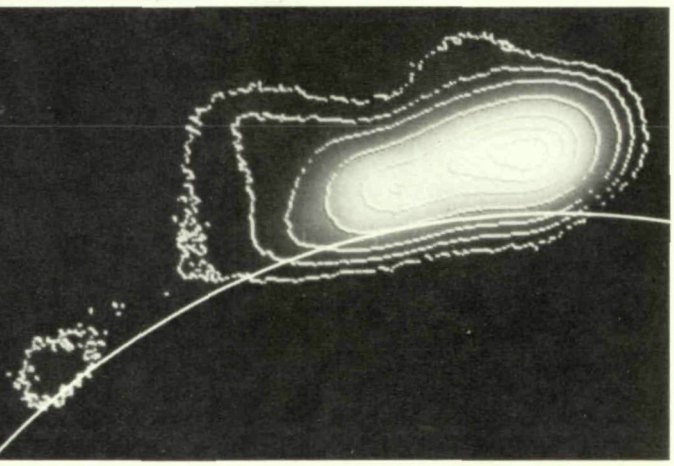

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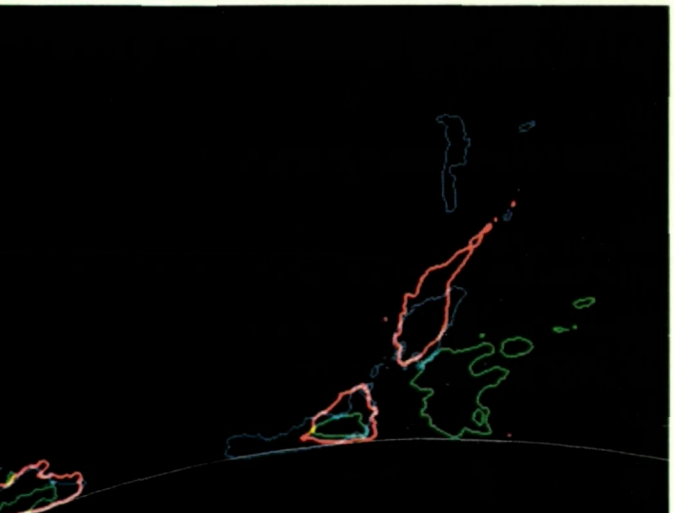

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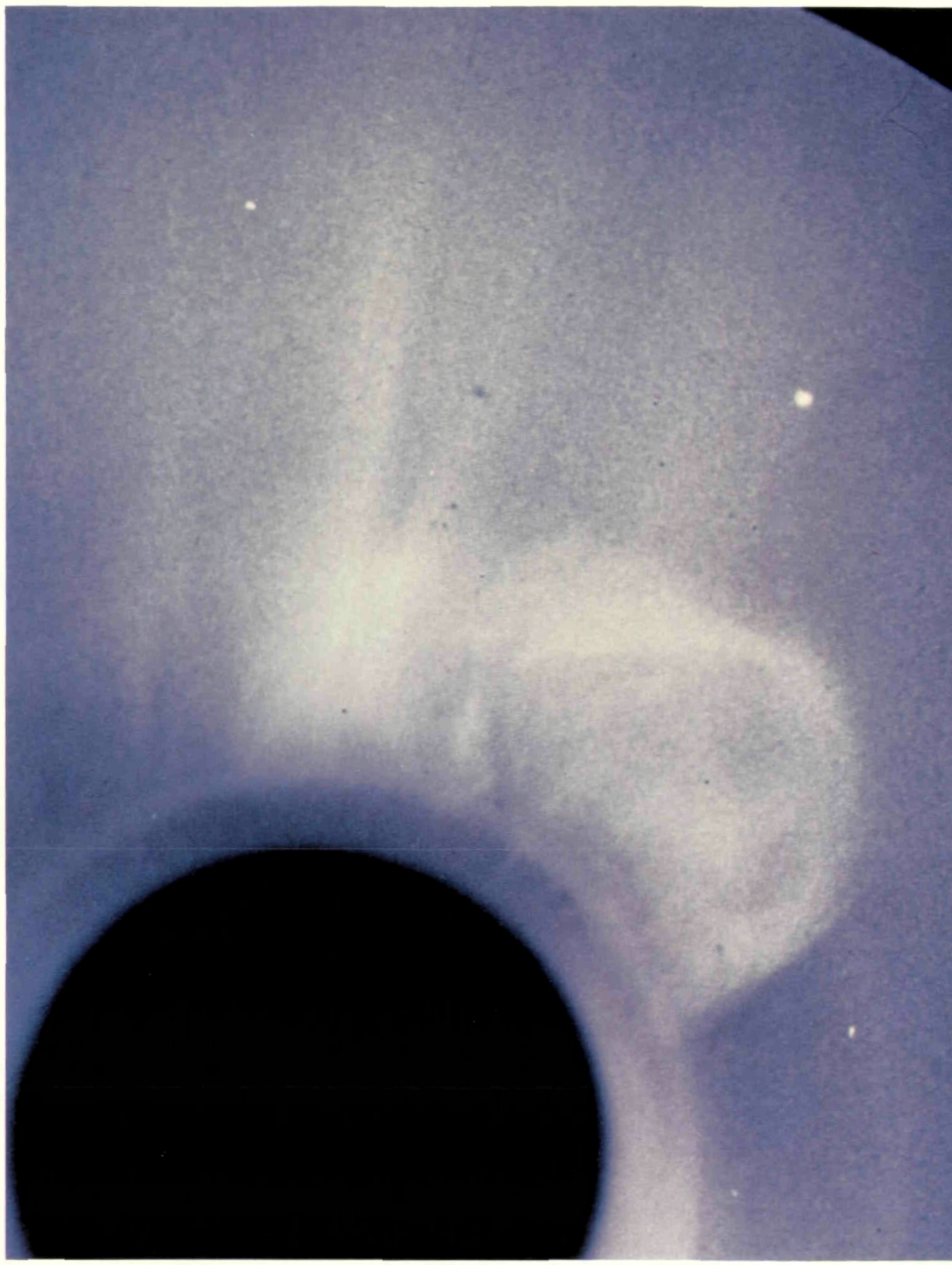

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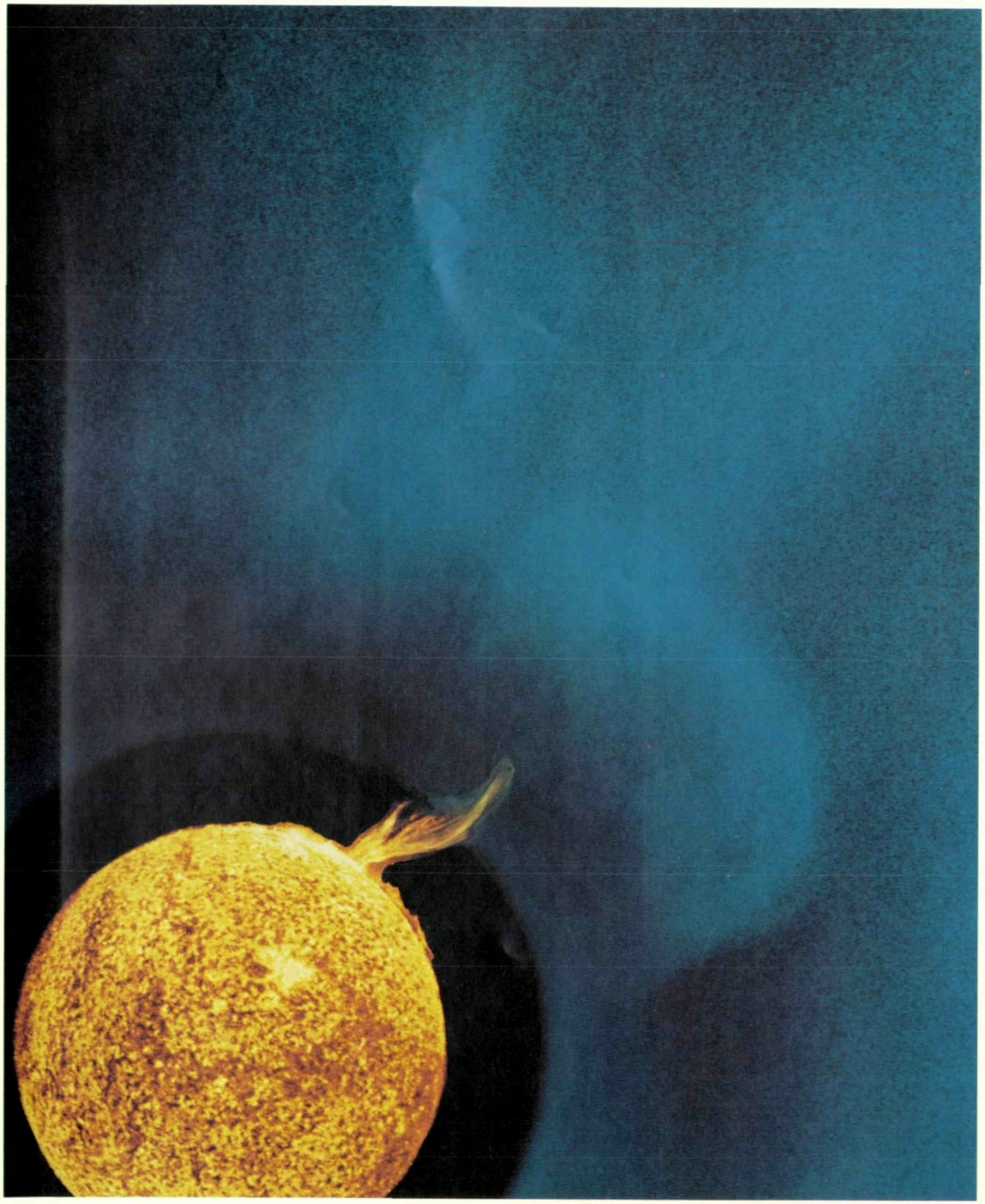

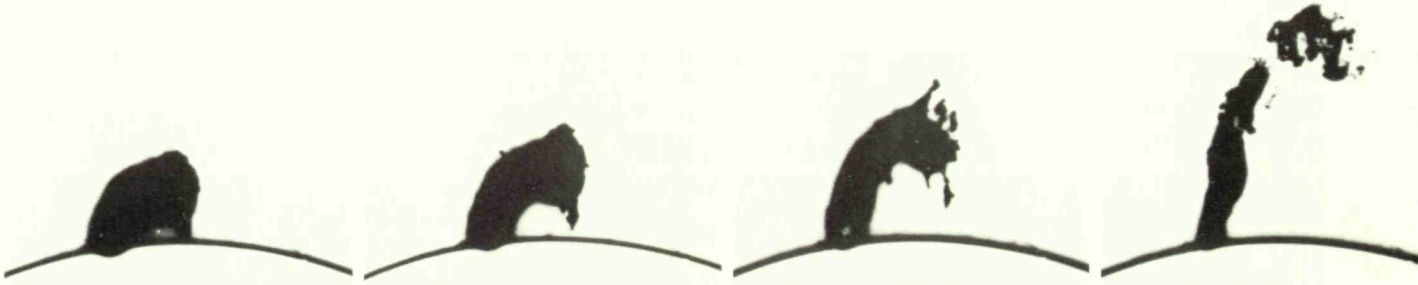

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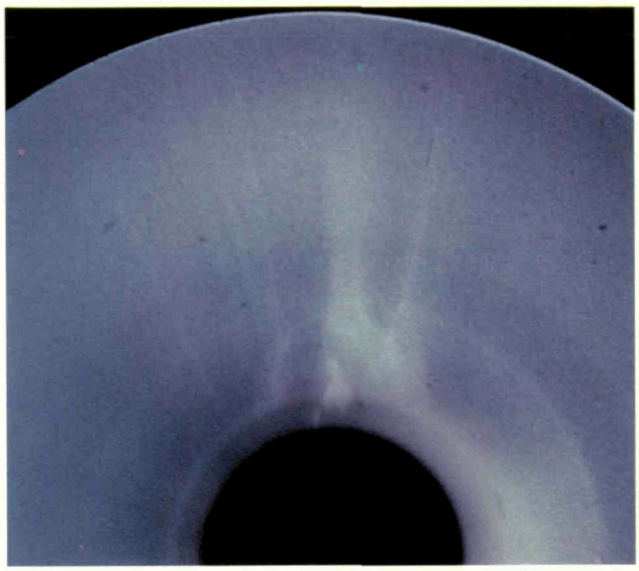

9

10

A LASHING PROMINENCE (1-8) whips a delicate disturbance through the gossamer form of the outer corona (9-12). Sequence (1-8), in H_α and ultraviolet light of helium, spans half an hour. The first coronal picture (9) was made at the same time as (6); in (12), an hour later, the coronal transient—a feature much brighter and more substantial than

5

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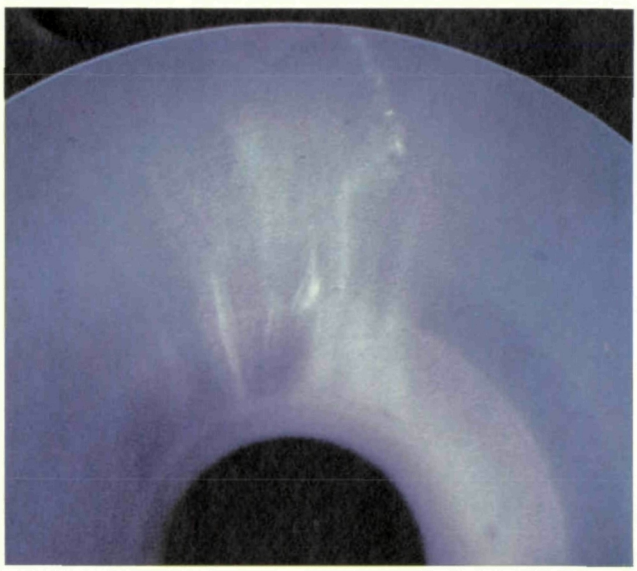
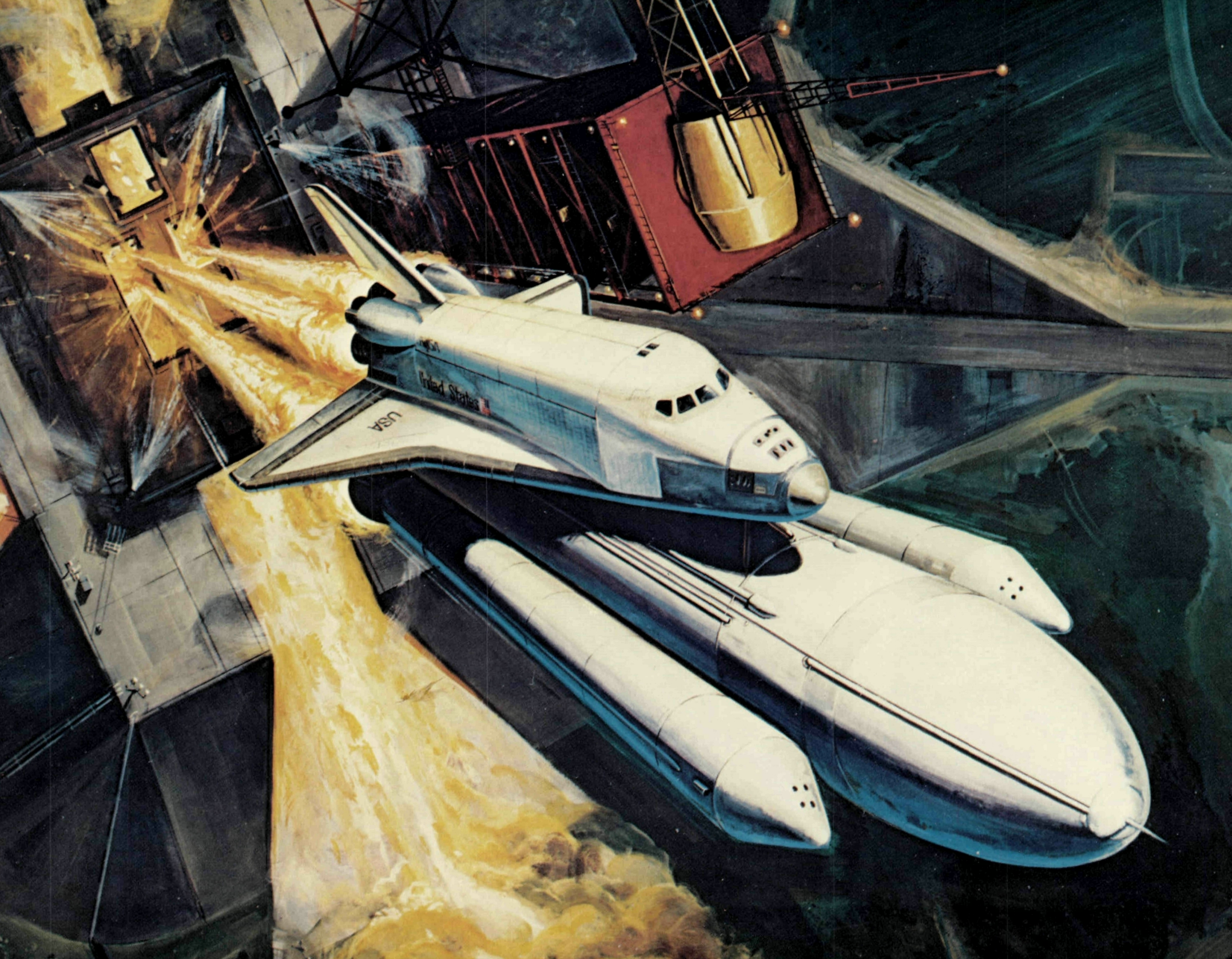


12

13

14

the diffuse, radial threads through which it travels—has sailed beyond the reach of the coronagraph, more than 3×10^6 km from the edge of the Sun. In (13,14), simultaneous images of the rupturing prominence, made in many wavelengths by Skylab's ultraviolet spectroheliograph, classify the fragments as the prominence flies apart.


United States
USA

8
A Look Ahead

We set sail on this new sea because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people.

John F. Kennedy, 1962

The Sun is at times serene—and sometimes violent—but always indispensable for life on Earth. How well do we know our Sun? What have we learned of it from Skylab that we did not know before? Are any major questions left unanswered? Are there any more surprises on the Sun?

By any yardstick Skylab's solar observations were an unqualified success, and probably the biggest step forward in all the centuries of man's efforts to understand our Sun and nearest star. Nine men brought back to Earth, in three Pacific splashdowns, a treasure trove of new knowledge of the Sun that has resolved fundamental questions about the most important object in the sky. Their efforts have changed the path of research in a field that was mature and presumably well understood when Skylab's fiery rocket left the sands of Florida for the sky.

Changes in solar astronomy followed almost instantly because the tightly organized Skylab program disseminated new results immediately to scientists around the world. When Skylab's last crew landed, on February 8, 1974, solar data from their program had already become a keystone in modern understanding of the Sun, much as the Apollo lunar findings almost instantly rewrote astronomical textbooks on the Moon. As with Apollo, the splashdown was but the beginning; since 1974 an ever increasing number of important new results have come from the Skylab data, and we have only begun to use them.

We now know of a host of previously hidden and important relationships between the separate layers of the solar atmosphere: how the various masks of the Sun—photosphere, chromosphere, transition region, and corona—are connected and related, for Skylab showed us these faces simultaneously, and in their many moods. We had never before had that observational advantage. For the first time Skylab allowed us an extended view, in sharp detail, of the mysterious outer atmosphere of the Sun. In X-ray wavelengths we saw the corona in full face, not just at the edges as was all that had been possible for previous generations of astronomers, who had been limited to observations during natural eclipses or observations with ground-based coronagraphs. It was the answer to a long-held dream of astronomers, who since Benjamin Franklin's day had followed the paths of solar eclipses to the ends of the world for a few minutes' look at this important layer of the Sun.

Skylab's X-ray photographs revealed the secrets of coronal holes, which were of necessity masked in eclipse views, and which may prove to be the most terrestrially important of all solar phenomena. The quick responses of Skylab's astronaut observers, coupled with its unequaled instrumentation, caught at last the secrets of the start of solar flares, another feature of profound terrestrial importance. X-ray and ultraviolet pictures of early stages of flares from Skylab force a reappraisal of old concepts of these explosive events and demon-

strate that the visible light appearance of flares, which has been studied for generations, is but a late and perhaps unimportant phase of the real flare event, which comes earlier and higher in the solar atmosphere.

Skylab found a whole new realm of solar activity on a cosmic scale in coronal transients—the Sun's biggest show—great blobs of coronal matter, larger than the Sun itself, that stream outward past the planets dwarfing everything in their path. We may presume that the Sun has been blowing these gargantuan bubbles toward the planets for thousands of years; and yet their presence went almost unnoticed and largely unseen until the time of Skylab.

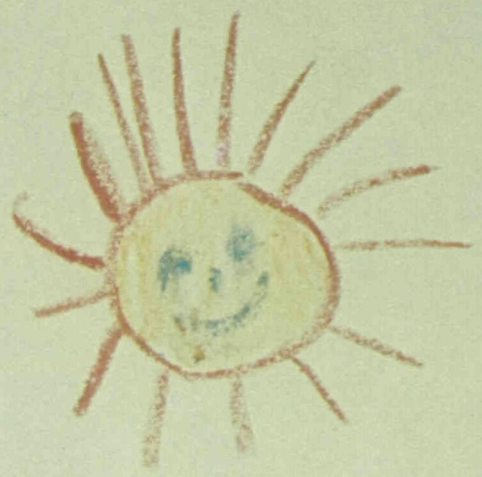
Thanks to Skylab's ultraviolet and X-ray cameras we now know about another new sign of action on the Sun—bright points in the corona and upper chromosphere that may well prove to be more fundamental than the more obvious signs of magnetic activity, like sunspots, which have for so long dominated our attention. It seems safe to predict that from continued studies of all these newfound features will come the sorts of advances which followed Galileo's first detailed looks at sunspots or Hale's monochromatic pictures of the chromosphere.

Yet any look at history warns us how wrong we can be in attempting to assess the progress of our own generation in learning about nature. That assessment seems better reserved for retrospect, and the longer the view the better. Then, almost invariably, the path of progress proves different from what it seemed along the way: not a beeline from one discovery to another, but a twisting and tortuous path with as many false starts as good ones. Truth is elusive, and meaningful science was never easy.

Some contend that science and learning advance largely through revolutions in which previously held truths are overturned by new evidence or new inquiry. If that is so, we can still be certain that in solar physics Skylab was such a turning point, and a source of a wholly new and clearer picture of the Sun.

We can be even more certain that all the questions are not yet answered, or even asked, nor all the surprises found. Skylab gave us a detailed look at the Sun during only one phase of its varied behavior, near the minimum of the 11-yr solar cycle. What are the natures of coronal holes, coronal transients, and bright points when the Sun is at the maximum of its well-known activity cycle? What is the cause of the 11-yr cycle of sunspots and of more anomalous times when solar activity seems to disappear altogether from the Sun? How constant is the Sun? Solar variation clearly affects our upper atmosphere, producing the aurora borealis, distortions of our magnetic field, and changes in our ionosphere. Do these or other changes on the Sun affect short-term weather or long-term climate on Earth? And if so, which solar changes, and how? What powers the Sun? How long will that fuel source last, and how constantly will it burn? Are our theories of the solar interior (which no one has ever seen) correct, or, as so often is the case, only a present approximation in the winding path toward truth?

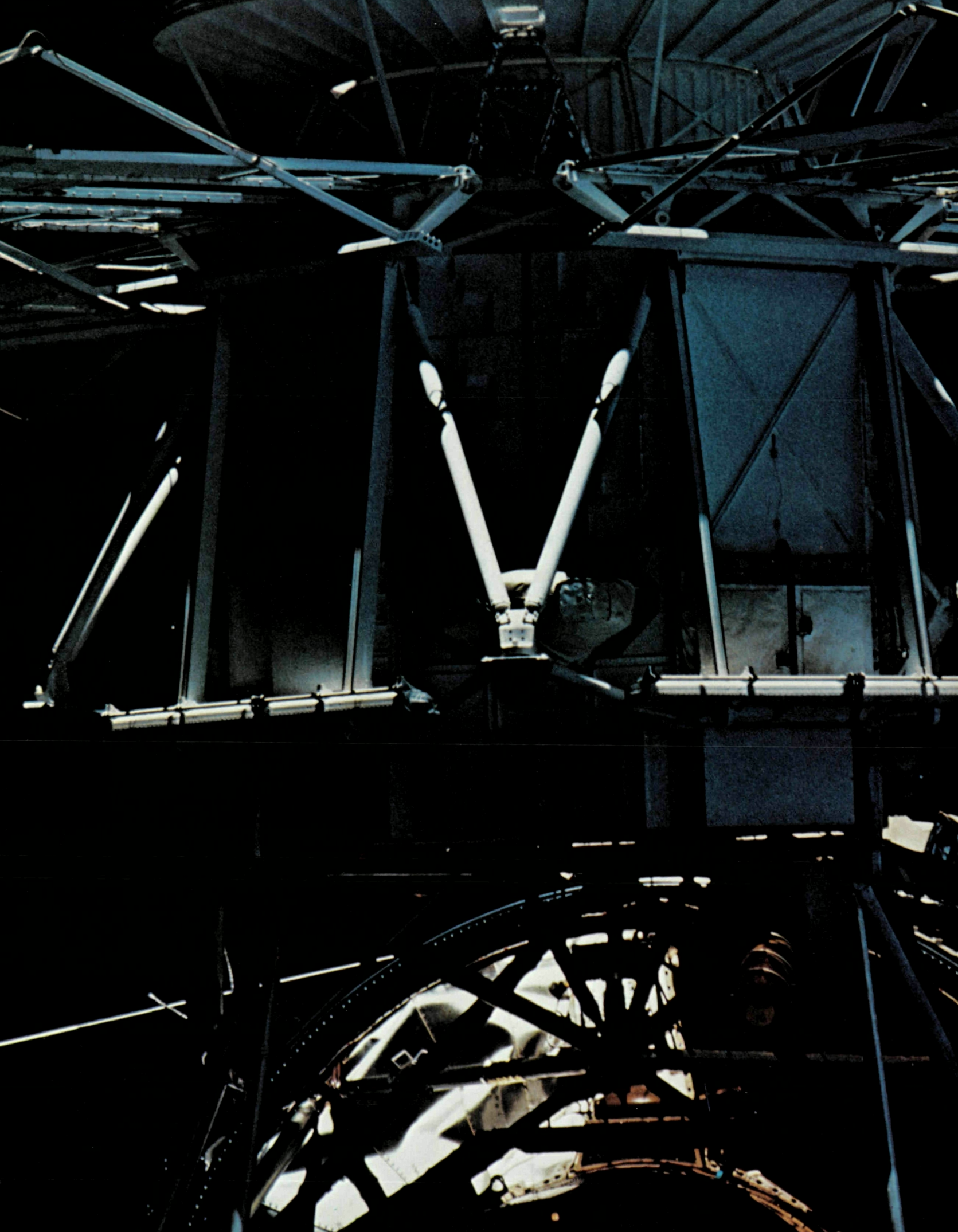
Skylab seems certain to confirm another lesson from history: that from every new instrument and endeavor in science we can expect a few answers and many more new questions. So it was with Galileo's small refractor and with Tycho Brahe's great astronomical quadrant instrument before that. Our pictures of a new Sun from Skylab have answered urgent questions but they, too, will raise a host of new ones. It is the way we learn, and it is not so much the answers as the questions that lead us toward a better understanding of the all-important Sun.



The Sun

how did the sun
get in her place
with her round & shiny
happy face who casts
the shadows high &
low. I do not know, I do not know.

AMY EDDY, age 7.



Editor's Note

The amount of new scientific data about our Sun obtained by Skylab and its crews is indeed impressive by any scale. However, not until one sees a comprehensive profile of the results under one cover and compares them with the observations man has been able to accomplish before in all of history, does the full magnitude of this scientific achievement come clearly into focus. Skylab and the Apollo Telescope Mount were a triumph for the scientists, a great accomplishment for the engineers and managers, and a challenge to the astronauts.

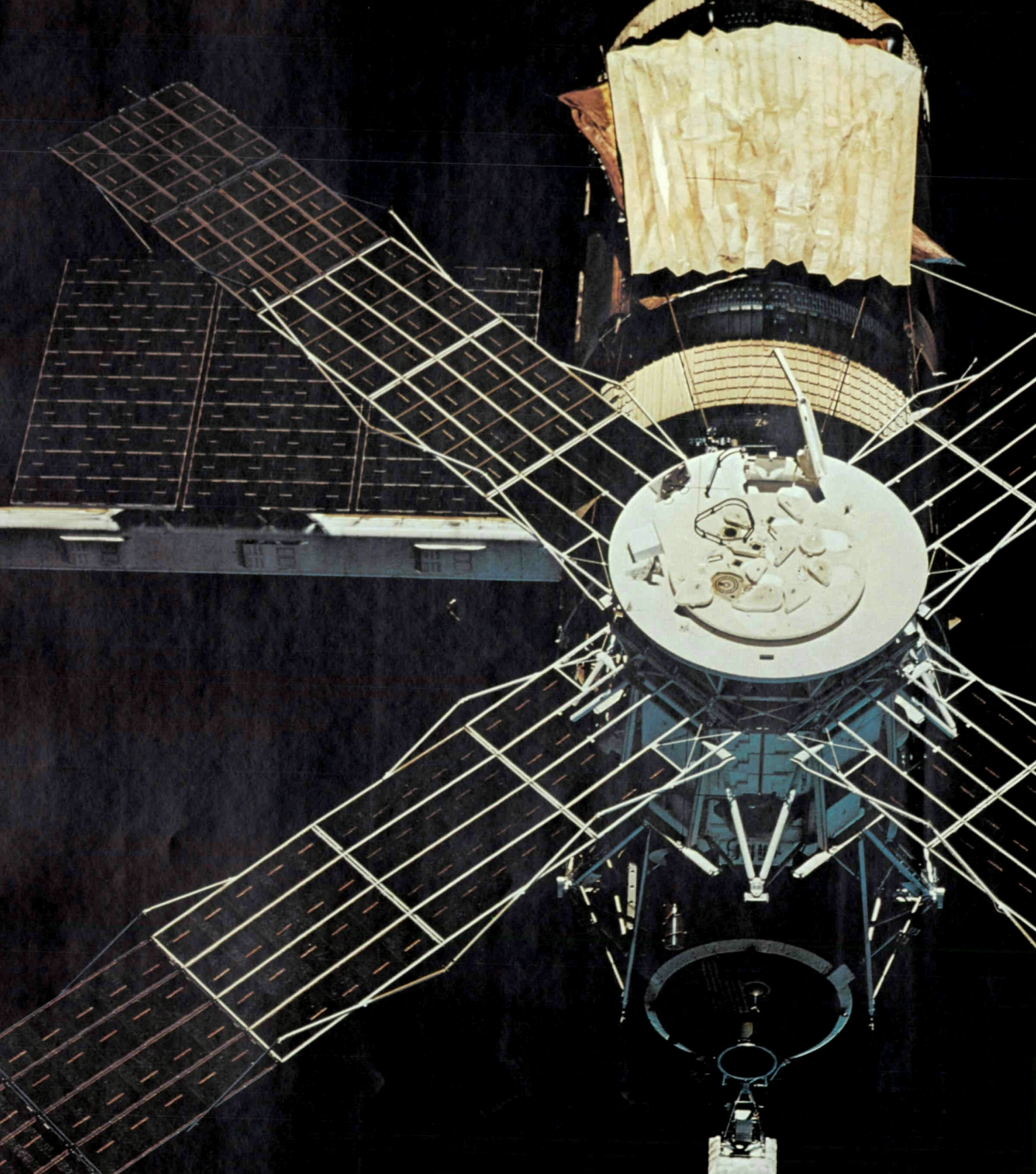
None of this would, of course, have been possible without the perseverance and dedication of the solar science community and, in particular, the principal investigators who provided the necessary planning and impetus for the Apollo Telescope Mount project. Their efforts, in combination with the engineers, technicians, and other personnel in Government, industry, and the academic community, brought the initial concepts into reality and produced the exceptional instrumentation and other hardware that were so essential to providing the desired results.

This volume highlights the key findings of Skylab by emphasizing pictorial results that not only show some of the striking features never seen before but also clearly reflect the new detail and dimension revealed about our Sun by Skylab instrumentation. For further analysis and scientific interpretation of these data, and the tens of thousands of additional pictures and other information returned from orbit, the reader is referred to the scientific publications and presentations by the principal investigators, coinvestigators, and other collaborators. (ATM scientific publications and presentations published through February 1977 are listed in NASA TMX-73300 entitled "Apollo Telescope Mount—A Partial Listing of Scientific Publications and Presentations" and in NASA TMX-73393, in Supplement 1 to NASA TMX-73300.)

The basic concept and manuscript for this book was prepared by John A. Eddy of the High Altitude Observatory, National Center for Atmospheric Research (sponsored by the National Science Foundation), who was assisted by N. Paul Patterson and Halka Chronic. Skylab solar photographs were provided by the Skylab ATM principal investigators, with special help from Joan Vorpahl, Leon Golub, Randolph Levine, Jesse Smith, Brian Dohne, and Adam Csoeke-Poeck. Guidance and technical counsel were provided by an editorial board chaired by Gordon A. Newkirk, Jr. The original layout was by Harry R. Melson.

This book is offered as a grateful tribute to the thousands of people who worked on or supported the solar investigations on Skylab. Their efforts have provided a new horizon for the study of our Sun.

REIN ISE
Apollo Telescope Mount Project Manager
Marshall Space Flight Center



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Page	Identification	Ion	Wavelength[1]	Date	Time	Source
Cover	–	–	–	–	–	MSFC
ii, v	–	–	–	–	–	CIT and CI of Washington
vi	–	–	–	–	–	NOAA
viii	–	–	–	–	–	SPO
x	–	–	–	–	–	SPO
xvi/xvii	Bottom	–	–	–	–	*National Geographic Magazine* (copyrighted; photo by Michael Laughton)
xx	–	–	–	–	–	CIT and CI of Washington
4	–	–	–	–	–	Gary Emerson
6	–	–	–	–	–	ASFO
8	–	–	–	–	–	*Natural History Magazine*
9	–	–	–	–	–	Houghton Library, Harvard University
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14/15	Top	–	–	–	–	Harry Melson
15	–	–	–	–	–	BBSO
16	Top	–	–	–	–	SPO
19	–	–	–	–	–	SPO
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22	–	–	–	–	–	Mt. Wilson Observatory
23	–	–	–	–	–	BBSO
24	–	–	–	–	–	Bruce Gillespie, KPNO
25	–	–	–	–	–	BBSO
26	–	–	–	–	–	HAO
28	Bottom	–	–	–	–	KPNO
29	–	–	–	–	–	Tersch Enterprises
30	–	–	–	–	–	John U. Free
31	Bottom	–	–	–	–	William C. Atkinson
32	Top	–	–	–	–	HCO
33	Top	–	–	–	–	Dartmouth College
	Center	–	–	–	–	Lick Observatory
34	–	–	–	–	–	U.S. Naval Observatory
40/41	–	–	–	–	–	Emily Chronic
42	–	–	–	–	–	R. Tousey, NRL

See footnotes at end of table.

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
44	–	–	–	–	–	Princeton University Observatory
53	Left	–	–	–	–	AS&E
	Right	–	–	–	–	Ball Aerospace Systems
54	Left	–	–	–	–	Ball Aerospace Systems
	Right	–	–	–	–	Ball Aerospace Systems
55	–	–	–	–	–	Perkin Elmer Corp.
60	–	He (II)	304	–	–	NRL
63 to 65	–	H	6563	July 28 to Sept. 24, 1973	–	NOAA
66	–	H	6563	–	–	NOAA
68/69	–	–	–	–	–	HCO
70	1	Magnetogram	–	May 30, 1973	17:45	KPNO
	2	H	6563	May 30, 1973	11:28	Ramey Air Force Base
	3	Ca (II)	3934	May 30, 1973	20:06	University of Hawaii
	4	He (II)	304	May 30, 1973	14:14	NRL
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	6	O (VI)	1032	Jan. 5, 1974	–	HCO
	7	Mg (X)	625	Jan. 5, 1974	–	HCO
	8	Composite of 5 to 7	–	Jan. 5, 1974	–	HCO
72	1	Composite of 1 to 3	–	–	–	HCO
73	2	H	1216	Jan. 28, 1974	–	HCO
	3	C (III)	977	Jan. 28, 1974	–	HCO
	4	Mg (X)	625	Jan. 28, 1974	–	HCO
	5, 6	He (II)	304	Jan. 28, 1974	11:56	NRL
		Fe (XV)	284	Jan. 28, 1974	11:56	NRL
74	1	He (II)	304	Dec. 22, 1973	23:12	NRL
	3	Mg (IX)	368	Dec. 23, 1973	02:15	NRL
75	2	Ne (VII)	465	Dec. 23, 1973	02:15	NRL
	4	Fe (XV)	284	Dec. 22, 1973	23:12	NRL
76	1	Composite of 2 to 4	–	Sept. 11, 1973	22:30	HCO
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	4	Mg (X)	346	Sept. 11, 1973	22:30	HCO
78	1	C (III)	977	May 29, 1973	–	HCO
	2	O (VI)	1032	May 20, 1973	–	HCO
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	4	Ne (VII)	465	Aug. 19, 1973	–	NRL
79	5	C (III)	977	Jan. 28, 1974	–	HCO
	6	Ne (VII)	465	Dec. 15, 1973	16:56 to 22:01	HCO
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80/81	–	Mg (X)	625	Jan. 28, 1974	–	HCO
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	3	Ne (VII)	465	–	–	NRL
	4	Mg (IX)	368	–	–	NRL
84	1	–	–	Sept. 21, 1922	–	Lick Observatory
85	2	Mg (IX)	368	Dec. 30, 1973, to Jan. 5, 1974	–	NRL
86	1	C (III)	977	Dec. 11, 1973	22:56 to 23:10	HCO
86/87	2	C (III)	977	Dec. 11, 1973	22:56 to 23:10	HCO

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
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87	3	–	X-ray	–	–	AS&E and HCO
88/89	–	–	X-ray	Jan. 21, 1974	17:23	MSFC and Aerospace Corp.
90	1	–	X-ray	June 30, 1973	–	AS&E and HCO
	3	–	X-ray	Oct. 15, 1963	–	AS&E
	4	–	X-ray	Mar. 7, 1965	–	AS&E
91	2	–	WL	June 30, 1973	–	HAO
	5	–	X-ray	June 8, 1968	–	AS&E
	6	–	X-ray	Nov. 4, 1969	–	AS&E
92	1	–	X-ray	June 1, 1973	–	AS&E and HCO
93	2	–	X-ray	May 31, 1973	–	HCO and AS&E
94	1	–	X-ray	June 16, 1973	–	AS&E and HCO
	2	Fe (XVI)	335	June 16, 1973	17:55	NRL
95	3	–	X-ray	June 16, 1973	21:07	MSFC and Aerospace Corp.
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96	2	–	XUV	Aug. 15, 1973	–	NRL
97	–	–	X-ray	June 1 to Oct. 8, 1973	–	AS&E and HCO
98/99	–	–	X-ray	Aug. 21, 1973	–	HCO and AS&E
100	1	–	XUV	Aug. 20, 1973	–	NRL
101	2	He (II)	304	Aug. 21, 1973	–	NRL
	3	–	X-ray	Aug. 21, 1973	–	AS&E and HCO
102	1	–	X-ray	June 28, 1973	–	AS&E and HCO
103	2	Mg (X)	625	Jan. 28, 1974	15:06, 16:32, 17:16	HCO
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	5	–	X-ray	Aug. 21, 1973	–	AS&E and HCO
	6	–	X-ray	Sept. 17, 1973	–	AS&E and HCO
105	3	–	X-ray	Aug. 23, 1975	13:28	AS&E and HCO
	4	–	X-ray	Aug. 25, 1973	12:26	AS&E and HCO
	7, 8	–	X-ray	–	–	AS&E and HCO
106/107	–	–	–	–	–	HCO
108	–	He (II)	304	Nov. 30, 1973	–	NRL
109	–	He (II)	304	Dec. 1, 1973	–	NRL
110	1	H	1216	Aug. 30, 1973	14:01	HCO
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111	6	–	X-ray	Sept. 1, 1973	19:47	AS&E and HCO
112	1	Mg (X)	625	July 2, 1973	00:57	HCO
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114	1	Composite:		July 2, 1973	22:39	HCO
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		Blue = Mg (X)	625			

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
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		Green = C (III)	977			
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	4	Ne (VII)	465	–	–	NRL
	5	Mg (IX)	368	–	–	NRL
	6	Si (XII)	499	–	–	NRL
	7	Fe (XV)	284	–	–	NRL
116/117	–	–	WL	–	–	HAO
118	1	–	WL	June 1, 1973	–	HAO
	2	–	X-ray	June 1, 1973	–	AS&E and HCO
119	3	Composite of 1 and 2	–	–	–	HAO and AS&E
	4-6	–	WL	–	–	HAO
120	1	–	WL	June 6, 1973	10:52	HAO
121	2	–	WL	June 19, 1973	22:11	HAO
122	1	–	WL	Sept. 16, 1973	12:32	HAO
	2	–	WL	Oct. 13, 1973	13:52	HAO
	3	–	WL	Nov. 9, 1973	12:44	HAO
	7	–	WL	July 2, 1973	04:30	HAO
	8	–	WL	July 15, 1973	14:00	HAO
	9	–	WL	July 29, 1973	04:35	HAO
123	4	–	WL	Dec. 7, 1973	06:54	HAO
	5	–	WL	Jan. 3, 1974	12:10	HAO
	6	–	WL	Jan. 31, 1974	00:47	HAO
	10	–	WL	June 20, 1973	21:30	HAO
	11	–	WL	June 22, 1973	12:15	HAO
	12	–	WL	June 24, 1973	03:39	HAO
124	1	–	WL	June 30, 1973	11:44	HAO
	2	–	WL	June 30, 1973	11:52	HAO
	3	–	WL	June 30, 1973	11:56	HAO
	4	–	WL	June 30, 1973	12:00	HAO
	6	–	–	–	–	HAO
125	–	–	WL	June 30, 1973	–	HAO
126	–	H	6563	–	–	NOAA
127	–	H	6563	–	–	SPO
128/129	–	Composite:		Jan. 28, 1974	–	HCO
		Blue = H	1216			
		Red = C (III)	977			
		Green = Mg (X)	625			
130	1	–	X-ray	June 1, 1973	–	AS&E and HCO
	2	Mg (X)	625	Jan. 28, 1974	–	HCO
	3	–	X-ray	–	–	AS&E and HCO
131	4	Blue = C (II)	1335	Aug. 21, 1973	–	HCO
		Red = O (VI)	1032			
		Green = Mg (X)	625			
	5	Magnetogram	–	Aug. 21, 1973	–	KPNO
132	1	–	X-ray	Jan. 13, 1974	14:06	MSFC and Aerospace Corp.
	2	–	X-ray	Jan. 13, 1974	14:08	MSFC and Aerospace Corp.
	3	–	X-ray	Jan. 13, 1974	14:09	MSFC and Aerospace Corp.
	7	–	X-ray	–	–	AS&E and HCO
	8	–	X-ray	Jan. 12, 1974	13:30	AS&E and HCO
	9	–	X-ray	Jan. 12, 1974	13:42	AS&E and HCO
	10	–	X-ray	Jan. 12, 1974	13:53	AS&E and HCO
133	4	–	X-ray	Jan. 13, 1974	14:14	MSFC and Aerospace Corp.
	5	–	X-ray	Jan. 13, 1974	14:18	MSFC and Aerospace Corp.

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
	6	–	X-ray	Jan. 13, 1974	14:23	MSFC and Aerospace Corp.
	11					
	Top	Mg (X)	625	Aug. 21, 1973	05:30, 05:35, and 05:41	HCO
	Middle	O (VI)	1032	Aug. 21, 1973	05:30, 05:35, and 05:41	HCO
	Bottom	H	1216	Aug. 21, 1973	05:30, 05:35, and 05:41	HCO
134/135	–	Red = Mg (X)	625	Dec. 4, 1973	–	HCO
		Green = O (VI)	1032			
		Blue = O (IV)	554			
136	1	–	–	Sept. 6, 1973	02:21	MSFC and Aerospace Corp.
137	2	–	X-ray	Sept. 5, 1973	–	AS&E and HCO
	3	Magnetogram	–	Sept. 5, 1973	–	KPNO
	4	–	X-ray	Sept. 4, 1973	–	MSFC and Aerospace Corp.
	5	–	–	Sept. 4, 1973	00:55	Aerospace Corp.
138	–	Ne (VII)	465	Aug. 14, 1973	–	NRL
139	Top left	O (VI)	1032	Dec. 4, 1973	–	HCO
	Top right	Blue = H	896	June 30, 1973	–	HCO
		Red = Ne (VII)	465			
	Bottom	Green = Mg (X)	625	Nov. 24, 1973	02:14 to 02:24	HCO
		Blue = Si (XII)	518			
		Red = Ne (VII)	463			
140	1-4, 6-8	–	X-ray	–	–	AS&E and HCO
	5	Magnetogram	–	–	–	KPNO
141	9	H	349	Sept. 11, 1973	22:15	HCO
	10	Ne (VII)	465	Sept. 11, 1973	22:15	HCO
	11	Si (XII)	521	Sept. 11, 1973	22:15	HCO
	12	Composite of 9 to 11	–	Sept. 11, 1973	22:15	HCO
142	1	–	X-ray	Sept. 1, 1973	01:13	MSFC and Aerospace Corp.
	2	–	X-ray	Sept. 2, 1973	00:34	MSFC and Aerospace Corp.
	3	–	X-ray	Sept. 2, 1973	13:16	MSFC and Aerospace Corp.
	4	Magnetogram	–	Sept. 1, 1973	14:48	KPNO
	5	Magnetogram	–	Sept. 2, 1973	07:01	KPNO
	6	–	X-ray	Sept. 4, 1973	00:46	MSFC and Aerospace Corp.
	7	–	X-ray	Sept. 4, 1973	13:16	MSFC and Aerospace Corp.
	8	Magnetogram	–	Sept. 4, 1973	15:19	KPNO
143	9	Magnetogram	–	–	–	KPNO
	10-12	–	X-ray	–	–	AS&E and HCO
	13-15	H	6563	–	–	MSFC
144/145	–	He (II)	304	June 15, 1973	14:13	NRL
146	1	H	6563	Aug. 7, 1972	–	SPO
147	2	H	6563	Sept. 7, 1973	12:22	MSFC
	3	H	6563	Dec. 17, 1973	00:36	MSFC
	4	H	6563	Sept. 10, 1973	02:37	MSFC
	5	H	6563	Sept. 5, 1973	20:26	MSFC
	6	H	6563	Aug. 9, 1973	15:54	MSFC
	7	H	6563	June 15, 1973	–	MSFC

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
148	1	–	X-ray	Aug. 29, 1973	18:36	AS&E and HCO
149	2	–	263 to 304	–	–	NRL
	3, 4	Fe (XVI)	263	–	–	NRL
		Fe (XIV)	265			
	5	Fe (XVI)	263	Jan. 15, 1973	–	NRL
		Fe (XXIII)	263.7			
		Fe (XIV)	264.8			
	6	Fe (XXIV)	192.1	Jan. 15, 1973	–	NRL
		Ca (XVII)	192.9			
150	1	O (VI)	1032	Nov. 23, 1973	07:18	HCO
	2	O (VI)	1032	Nov. 23, 1973	07:24	HCO
	3	O (VI)	1032	Nov. 23, 1973	07:29	HCO
	4	O (VI)	1032	Nov. 23, 1973	07:35	HCO
	5	O (VI)	1032	Nov. 23, 1973	07:41	HCO
	6	Composite:		Nov. 23, 1973	07:35	HCO
		Blue = C (II)	1335			
		Green = O (VI)	1032			
		Red = Mg (X)	625			
151	7	–	X-ray	Sept. 5, 1973	18:30	MSFC and Aerospace Corp.
	8	Fe (XVI)	335	Sept. 5, 1973	18:37	NRL
	9	H	6563	Sept. 5, 1973	–	NOAA
152/153	1	–	190 to 350	June 15, 1973	14:13	NRL
152	2	–	1150 to 1950	June 15, 1973	–	NRL
153	3	–	X-ray	Aug. 6, 1973	02:08	AS&E and HCO
	4	–	1523 (at left) to 1553 (at right)	–	–	NRL
	5	–	1523 (at left) to 1553 (at right)	–	–	NRL
154	Left	O (IV)	554	Jan. 26, 1974	02:24	HCO
154/155	Center	O (VI)	1032	Jan. 26, 1974	02:24	HCO
155	Right	Mg (X)	625	Jan. 26, 1974	02:24	HCO
156/157	–	He (II)	304	Aug. 9, 1973	–	NRL
		Fe (XV)	284			
158	1	H	1216	Jan. 2, 1974	23:58	HCO
	2	O (IV)	554	Jan. 2, 1974	23:58	HCO
	3	Mg (X)	625	Jan. 2, 1974	23:58	HCO
	4	Composite	–	Jan. 2, 1974	23:58	HCO
	5	H	1216	Sept. 12, 1973	10:44	HCO
	6	O (VI)	1032	Sept. 12, 1973	10:44	HCO
	7	Mg (X)	625	Sept. 12, 1973	10:44	HCO
	8	Composite of 5 to 7	–	Sept. 12, 1973	10:44	HCO
159	9	He (II)	304	Aug. 26, 1973	23:45	NRL
	10	H	6563	Nov. 13, 1973	23:20	AS&E and HCO
	11	H	6563	Nov. 14, 1973	13:18	AS&E and HCO
	12	–	X-ray	Nov. 13, 1973	21:55	AS&E and HCO
	13	–	X-ray	Nov. 14, 1973	15:15	AS&E and HCO
160	1	Composite:		Oct. 9, 1973	15:08	HCO
		Red = H	1216			
		Blue = Mg (X)	625			
		Green = O (IV)	554			
	2	Composite:		Oct. 9, 1973	15:13	HCO
		Red = H	1216			
		Blue = Mg (X)	625			
		Green = O (IV)	554			

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
	3	Composite:		Oct. 9, 1973	15:19	HCO
		Red = H	1216			
		Blue = Mg (X)	625			
		Green = O (IV)	554			
	4	Composite:		Oct. 9, 1973	15:25	HCO
		Red = H	1216			
		Blue = Mg (X)	625			
		Green = O (IV)	554			
	5	Composite:		Oct. 9, 1973	15:30	HCO
		Red = H	1216			
		Blue = Mg (X)	625			
		Green = O (IV)	554			
	6	He (II)	304	June 10, 1973	–	NRL
161	7	Red = H	1216	Sept. 12, 1973	11:11	HCO
		Green = C (III)	977			
		Blue = O (IV)	554			
	8	Red = H	1216	Sept. 12, 1973	14:15	HCO
		Green = C (III)	977			
		Blue = O (IV)	554			
	9	Red = H	1216	Dec. 14, 1973	11:27	HCO
		Blue = O (VI)	1032			
		Green = Mg (X)	625			
	10	Red = H	1216	Dec. 14, 1973	12:01	HCO
		Blue = O (VI)	1032			
		Green = Mg (X)	625			
	11	H	1216	Dec. 14, 1973	Red = 11:27 Green = 12:01	HCO
	12	O (VI)	1032	Dec. 14, 1973	Red = 11:27 Green = 12:01	HCO
	13	Mg (X)	625	Dec. 14, 1973	Red = 11:27 Green = 12:01	HCO
	14	H	1216	Dec. 14, 1973	Red = 11:27 Green = 11:44 Blue = 12:01	HCO
162	1	Composite of 6, 7, and 8	–	Dec. 19, 1973	04:43	HCO
	5	He (II)	304	Dec. 19, 1973	06:32	NRL
163	2	Composite of 6, 7, and 8	–	Dec. 19, 1973	04:48	HCO
	3	Composite of 6, 7, and 8	–	Dec. 19, 1973	05:32	HCO
	4	Composite of 6, 7, and 8	–	Dec. 19, 1973	05:55	HCO
	6	H	1216	Dec. 19, 1973	04:43	HCO
	7	C (III)	977	Dec. 19, 1973	04:43	HCO
	8	Mg (X)	625	Dec. 19, 1973	04:43	HCO
	9	O (IV)	554	Dec. 19, 1973	06:50	HCO

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
164/165	1	He (II)	304	Jan. 10, 1974	–	NRL
	2	Ne (VII)	465	Jan. 10, 1974	–	NRL
	3	Fe (XV)	284	Jan. 10, 1974	–	NRL
166	Top row left	–	–	–	–	HCO
	3d row left	–	–	–	–	HCO
	4th row left	He (II)	304	June 10, 1973	–	NRL
	Top row right	–	–	–	–	HCO
	2d row right	–	–	–	–	HCO
	3d row right	He (II)	304	Aug. 21, 1973	–	NRL
	4th row right	Ne (VII)	465	June 30, 1973	–	HCO
167	Top row left	–	–	–	–	HCO
	2d row left	–	–	–	–	HCO
	3d row left	He (II)	304	Aug. 21, 1973	–	NRL
	4th row left	–	–	–	–	HCO
	Top row right	–	–	–	–	HCO
	2d row right	H	1216	Sept. 12, 1973	11:11	HCO
	3d row right	–	–	July 10, 1973	21:45 to 22:02	HCO
	4th row right	–	–	–	–	HCO
168/169	–	–	WL	June 10, 1973	–	HAO and MSFC
170	1	–	WL	June 10, 1973	08:28	HAO
	2	–	WL	June 10, 1973	09:30	HAO
	3	–	WL	June 10, 1973	09:41	HAO
	5	He (II)	304	June 10, 1973	–	NRL
171	4	–	WL	June 10, 1973	09:53	HAO
172	1	–	WL	Aug. 10, 1973	13:43	HAO
	2	–	WL	Aug. 10, 1973	14:24	HAO
	5	–	X-ray	Aug. 10, 1973	–	AS&E and HCO
173	3	–	WL	Aug. 10, 1973	14:42	HAO
	4	–	WL	Aug. 10, 1973	15:12	HAO
	6	–	WL	Sept. 7, 1973	11:18	HAO
	7	–	WL	Sept. 7, 1973	13:07	HAO
174	1	–	WL	Aug. 21, 1973	14:42	HAO
	2	–	WL	Aug. 21, 1973	14:51	HAO
	4	H	6563	Aug. 21, 1973	Green = 13:42 Red = 13:55 Blue = 14:06	MSFC
	5	–	X-ray	Aug. 21, 1973	14:45	MSFC and Aerospace Corp.
175	3	–	WL	Aug. 21, 1973	15:11	HAO
		He (II)	304	Aug. 21, 1973	–	NRL

Page	Identification	Ion	Wavelength[1]	Date	Time	Source
176	1	H	6563	Jan. 17, 1974	19:30	HAO
	2	H	6563	Jan. 17, 1974	19:31	HAO
	3	H	6563	Jan. 17, 1974	19:33	HAO
	4	H	6563	Jan. 17, 1974	19:38	HAO
	9	H	6563	Jan. 17, 1974	19:44	MSFC
	10	H	6563	Jan. 17, 1974	20:07	MSFC
176/177	13, 14	–	635 to 320	Jan. 17, 1974	–	NRL
177	5	H	6563	Jan. 17, 1974	19:42	HAO
	6	He (II)	304	Jan. 17, 1974	19:45	NRL
	7	H	6563	Jan. 17, 1974	19:52	HAO
	8	He (II)	304	Jan. 17, 1974	19:58	NRL
	11	–	WL	Jan. 17, 1974	20:22	HAO
	12	–	WL	Jan. 17, 1974	20:50	HAO

AS&E = American Science & Engineering
ASFO = Aerospace San Fernando Observatory
BBSO = Big Bear Solar Observatory
CI = Carnegie Institution
CIT = California Institute of Technology
HAO = High Altitude Observatory
HCO = Harvard College Observatory
KPNO = Kitt Peak National Observatory
MSFC = Marshall Space Flight Center
NOAA = National Oceanic and Atmospheric Administration
NRL = Naval Research Laboratory
SPO = Sacramento Peak Observatory
WL = white light
XUV = extreme ultraviolet

[1] Numbers are in units of 10^{-10} m.

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